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UNDERSTANDING COST AND SCHEDULE GROWTH IN ACQUISITION PROGRAMS

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July 1994

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PREFACE

This paper was prepared by the Institute for Defense Analyses (IDA) for the Office of the Director, Acquisition Policy and Program Integration under a task entitled "Indicators of Cost and Schedule Growth." The objective of the task is to describe cost and schedule growth patterns associated with the acquisition of selected major systems, identify reasons for the growth, and develop a way to predict growth in ongoing development and early production phases. This paper examines cost and schedule growth in tactical missile and tactical aircraft programs.

This work was reviewed within IDA by Stanley A. Horowitz, Thomas P. Frazier, and David R. Graham.

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A. BACKGROUND

Programs to acquire major weapon systems often end up taking longer and costing more than planned. The time required to design and develop major weapon systems has apparently lengthened, and weapon systems often exceed their planned development schedules.

Excessive schedules have two significant negative effects: U.S. forces may be left without needed capabilities and longer schedules often mean higher costs. Growth in the cost of weapon systems appears to be a chronic problem: 66 out of 82 programs examined by IDA in 1992 had experienced cost growth.

The defense acquisition community is concerned that programs to develop major weapon systems take too long and cost too much. Cost growth forces the DoD to revise budget plans, makes systems less affordable, and frequently erodes congressional support for acquisition programs. Given recent reductions in the money available for defense, the acquisition community needs a better understanding of the causes of cost and schedule growth, so that those plans can be made more realistic.

B. OBJECTIVE AND APPROACH

DoD asked IDA to describe cost and schedule growth patterns and to identify reasons for the growth. By looking at past programs, we examined hypotheses about what separates the kinds of programs completed on schedule and within cost plans from those that suffer from schedule and cost growth.

The study focused on tactical missiles and tactical aircraft. We developed both qualitative and quantitative relationships between cost growth and schedule growth in missile programs. In addition, we developed quantitative cost/schedule relationships for a small sample of tactical aircraft.

C. REASONS FOR COST AND SCHEDULE GROWTH

Cost and schedule growth for the tactical missiles in our sample were measured in development and in production. These measures showed a great deal of variability among the twenty programs examined. Programs took from 50 months to 137 months from Milestone II to inital operational capability. Only two of the tactical missile programs were finished on time. The program with the highest development schedule growth exceeded its plan by 180 percent. Two programs were completed under budget, while two others cost more than double their Milestone II plan.

Selected tactical missile programs were examined in more detail to determine the reasons for schedule and cost growth. Table S-1 summarizes the characteristics of programs with low and high levels of development schedule growth. Keys to preventing schedule growth in development are technical realism and willingness to make tradeoffs. Programs with high development schedule growth tended to underestimate technical difficulty. Two of the five programs with high development schedule growth also had high overall cost growth. However, in three of the five cases of high development schedule growth, a strictly phased approach (resolving problems in development when spending levels are low) appeared to result in lower levels of overall cost growth.

Table S-2 shows characteristics of missile programs with low or high total program cost growth. Keys to preventing overall cost growth are correctly estimating the degree of technical difficulty in the programs and maintaining the planned production schedule. Programs that employed a high degree of concurrency, that had to be dual-sourced for technical reasons or that were dual-sourced at less than full rate, had high cost growth. In one case, the threat of competition appeared to reduce costs.

Cost and schedule growth measures were also calculated for a sample of seven tactical aircraft. These measures are less dispersed than those for tactical missiles. The aircraft programs tended to receive more management attention and more protection from schedule stretch than the tactical missiles. The highest cost growth index for tactical aircraft was 1.40, versus 2.23 for the tactical missiles. In two cases (the F-14A and the AV-8B), programs were stretched in production but did not suffer from the high cost growth seen in the missile programs. In the case of the F-14A, this could have been due to a combination of early warning and the presence of the F-14D development program to cushion the blow. When the AV-8B was stretched out, the fact that the F/A-18 and F-15 programs were using the same plant may have helped to spread overhead costs and contain cost growth in the AV-8B program. The program with the highest production cost growth is the F/A-18, which exhibited production cost growth of 42 percent. Technical changes made late in the process contributed to its high cost growth.

Table S-1. Characteristics of Programs With High and Low Schedule Growth in Development

Program	Percentage growth	Characteristics
Low Growth		
TOW 2	0%	Follow-on system
Sidewinder AIM-9M	1%	Follow-on system to fulfill goals of AIM-9L Learned from unrealistic estimate of prior system
MLRS	6%	Urgent program Competitive prototype Requirements/schedule tradeoff made in favor of schedule
High Growth		
Phoenix AIM-54A	94%	Problems resolved in development, not allowed to spill over into production Testing delays Delays in aircraft platform
Maverick AGM-65D/G	98%	Funding cut slowed development, allowed technology to catch up Prototype Vigorous testing program
AMRAAM	129%	Prototype showed infeasibility of approach High concurrency, urgent program Rushed testing
Sidewinder AIM-9L	148%	Urgent program, with fly-before-buy strategy Technical problems, with increased development quantity Joint service program, with technical disagreements
Sparrow AIM-7F	180%	Underestimation of technical difficulty (vacuum tube to solid state) Vigorous testing program

Table S-2. Characteristics of Programs With Low and High Cost Growth in Total Program

Program	Percentage growth	Characteristics
Low Growth		
MLRS	-10%	Competitive prototype Requirement lowered because of time urgency Mulityear procurement, low stretch
Maverick AGM-65A	1%	Total package procurement with low concurrency Vigorous testing program Low stretch
TOW 2	-4%	Urgent modification program Foreign Military Sales Low stretch
Sidewinder AIM-9M	10%	Learned from schedule problems in AIM-9L program Urgent program, took its lumps in development Low stretch
High Growth		
AMRAAM	84%	Prototype showed infeasibility of approach High concurrency, rushed testing Stretched program, dual-sourcing
Phoenix AIM-54C	89%	High concurrency Dual-sourced for technical reasons Five years qualifying for two years of competition Needed funding for next generation
Sparrow AIM-7M	100%	Competitive prototype, low cost growth in development Needed funding for next generation
Sidewinder AIM-9L	123%	Crash program Dual-sourced fcr technical reasons Production stretch

D. RELATIONSHIP BETWEEN SCHEDULE GROWTH AND COST GROWTH

We also considered the relationship between schedule growth and cost growth. Does schedule growth necessarily lead to cost growth, or do other factors intervene? Is the relationship between cost growth and schedule growth different for different equipment types, or for different phases of the acquisition cycle?

In addition to examining the relationship between cost and schedule, we considered whether other variables affect cost growth:

- Are programs to develop completely new systems more prone to cost growth than programs to modify existing systems?
- Are "crash" programs inherently more susceptible to cost growth? Does concurrency (simultaneous or overlapping development and production) necessarily doom a program to high cost growth?
- How much does adherence to the planned production schedule influence cost growth in production? Do programs whose procurement is stretched out have higher costs?

In the case of tactical aircraft, the one program that was a modification of an existing system—the AV-8B—had low cost growth. However, tactical missile modifications frequently have very high cost growth. This may be because modifications are often made to the guidance and control system, the most expensive part of the missile.

Programs with time urgency had both high and low cost growth. Those with low cost growth used relatively simple technologies with careful testing and avoided production stretch. Concurrency was positively related to production cost growth, although the significance level was marginal (.12).

As indicated by the aircraft, production stretch need not necessarily lead to higher cost growth. In the cases of the F-14A and the AV-8B, plenty of warning and the ability to reallocate resources to other programs in the same plant helped to lessen cost growth. Without these mitigating factors, though, production schedule stretch usually leads to cost growth.

There were enough common factors in the tactical missiles to suggest that the estimation of quantitative relationships would be possible. The equations presented in this report relate cost growth to schedule growth in development and production. In development, a simultaneous model links an estimating relationship for schedule growth with a cost growth equation. The major determinant of development schedule growth was increase in quantity—the need to produce more items for testing than planned. Other variables in the DSG equation were the planned schedule for the program and dummy variables for intercept missiles and for one outlier. The results of this equation feed into a development cost growth equation. We also developed a simpler, single-equation alternative relating development cost growth to development schedule growth and development quantity growth. Cost growth in missile production was linked to schedule stretch, planned unit cost (a proxy for complexity), and multiyear procurement. Total program cost growth was related to total schedule growth, planned unit cost, and an intercept missile dummy variable. The total program cost growth equation is:

$$TPCG = .7645 + \underset{(.005)}{(.3677 \times TSG)} + \underset{(.04)}{(.1845 \times PUC)} + \underset{(.04)}{(.2729 \times IMD)}$$

$$\text{Adjusted } R^2 = .500 \qquad SEE = .259$$

where TPCG is total program cost growth, TSG is total schedule growth, PUC is planned unit cost in millions of 1994 dollars, and IMD is set equal to 1 for intercept missiles and 0 otherwise. Figure S-1 shows the fit of the total program cost growth equation for tactical missiles.

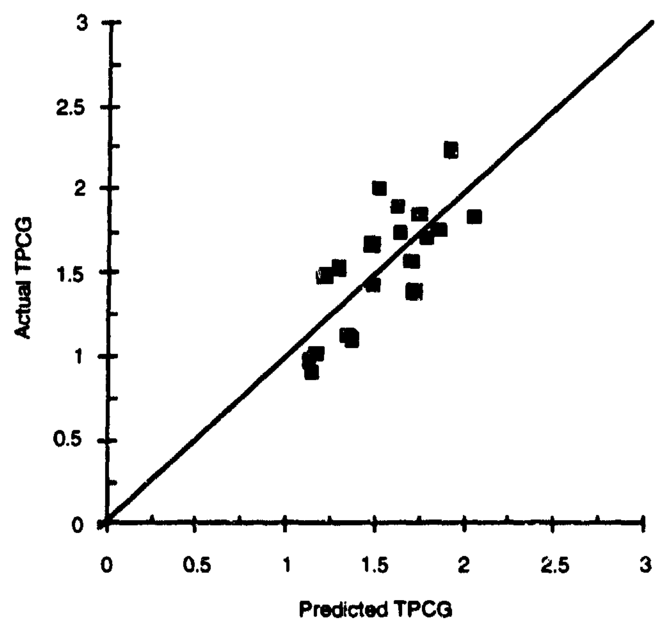

Figure S-1. Total Program Cost Growth for Tactical Missiles

Quantitative relationships were also developed for the aircraft, but the small sample size requires that they be regarded as tentative. In production and the total program, a logarithmic form using schedule length rather than schedule growth provided the best fit. The arithmetic form of the aircraft total program equation is:

$$\text{TPCG} = .3785 \times \underset{(.003)}{\text{ATS}^{.2365}} \times \underset{(.006)}{\text{EAV8B}^{-.3962}}$$

$$\text{Adjusted } R^2 = .890 \qquad \text{SEE} = .053$$

where TPCG is total program cost growth, ATS is actual total schedule, and EAV8B takes the value e for the AV-8B and 1 for all other aircraft. Numbers in parentheses below the coefficients are significance levels. A scatter plot of TPCG and ATS illustrating the fit of the equation is shown in Figure S-2.

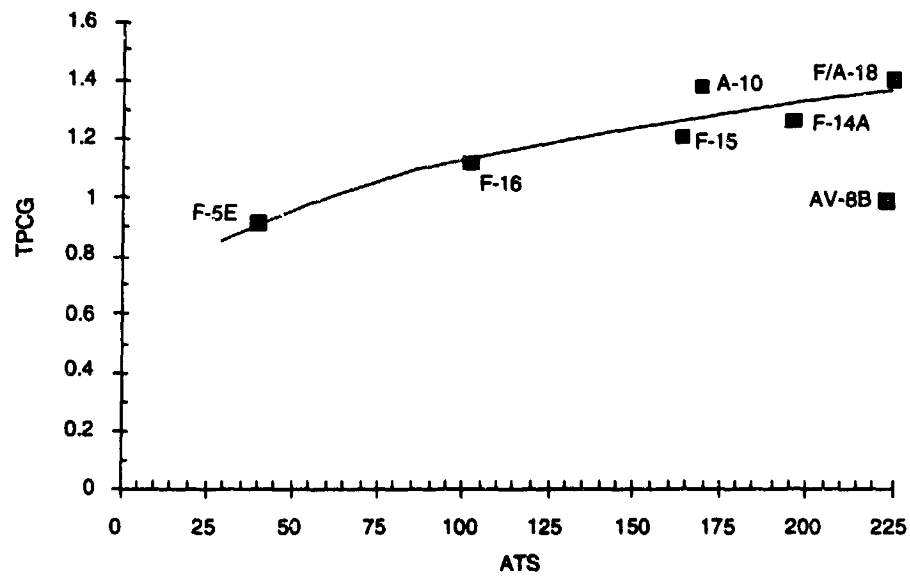

Figure S-2. Total Program Cost Growth for Tactical Aircraft

The tactical missile regressions generally fit well and can reasonably be used for getting a sense of the cost implications of schedule changes. Due to the small sample size, additional development work is needed to make the aircraft regressions into practical projection tools. This exercise indicated that the cost/schedule relationships probably look different for different equipment types.

E. IMPLICATIONS FOR DOD

In the light of these results, we conclude that DoD and other personnel who review acquisition programs would benefit from a review method based on detailed information about the strategies and outcomes of past programs. This is the first step for development of such a review method that examines the reasonableness of program plans and assesses the cost impact of schedule changes. The equations in this report can be used to identify programs likely to experience future growth, as well as to monitor the effect of schedule changes on cost growth. They can be used to identify which programs require more detailed examination.

The case analyses of tactical missiles also indicate that there are many useful lessons to be gleaned from historical perspective, lessons that cannot always be captured in a quantitative estimating relationship. For the tactical aircraft, the 1990s will be a decade where only a few prime contractors will survive. If programs are stretched out, contractors are not likely to be able to cushion the blow by working on other programs.

At the beginning of a weapon system development program, the feeling prevails that that program will avoid repeating the problems of previous programs. Yet cost and schedule growth persist. Despite individual differences in programs, the importance of understanding the level of technical difficulty when original schedule and cost estimates are made, of strict phasing and vigorous testing, and of adhering to production plans are borne out by analysis of past strategies and outcomes.

I. INTRODUCTION

A. BACKGROUND

Programs to acquire major weapon systems usually cannot follow their carefully-laid acquisition plans in every detail. They often end up taking longer and costing more than planned.

The time required to design and develop major weapon systems has apparently lengthened, and weapon systems often exceed their planned development schedules. A 1990 RAND Corporation study found that programs from the 1970s and 1980s took longer than those from the 1950s and 1960s. The demonstration/validation phase (from Milestone I to Milestone II in the process required by DoD regulations) and the engineering and manufacturing development phase (measured from Milestone II to the first delivery) each take about a year longer than they used to [1]. A 1992 IDA study found that, on average, systems take one-third longer than planned to progress from Milestone II to achievement of initial operational capability (IOC) [2].

Excessive schedules have two significant negative effects. One is that delays in schedules may leave U.S. forces without needed capabilities and vulnerable to enemy weapons, if the system is not completed on time. The other is that delays often translate into higher cost, which creates further problems.

Weapon system costs have been growing both from generation to generation, and, within a given system, from plan to realization. Growth in the cost of weapon systems appears to be a chronic problem. Of 82 programs examined by IDA in 1992, 66 had experienced cost growth [2].

The defense acquisition community is concerned that programs to develop major weapon systems take too long and cost too much. In 1986, the President's Blue Ribbon Commission on Defense Management (the "Packard Commission") called schedule length "a central problem from which most other acquisition problems stem" [3]. Cost growth forces the DoD to revise budget plans, makes systems less affordable, and frequently erodes congressional support for acquisition programs. Recent reductions in the money available for defense mean that the acquisition community needs to increase understanding of the reasons for deviations from program schedule and cost plans.

The large variations in total development time, in transition from development to production, and in schedule growth suggest that it is possible to reduce development times and to improve early estimates of schedules. Similarly, the large variation in cost growth—from little or no cost growth to more than double planned costs—suggests that potential exists for estimating costs more accurately. With a better understanding of the causes of cost and schedule growth, DoD can review program plans early in the process and make them more realistic.

B. PURPOSE AND APPROACH

IDA was asked by DoD to describe cost and schedule growth patterns and to identify reasons for the growth. By looking at past programs, we examined hypotheses about what separates the kinds of programs completed on schedule and within cost plans from those that suffer from schedule and cost growth. We also considered the relationship between schedule growth and cost growth. Does schedule growth necessarily lead to cost growth, or do other factors intervene? Is the relationship between cost growth and schedule growth different for different equipment types, or for different phases of the acquisition cycle?

In addition to examining the relationship between cost and schedule, we considered whether other variables affect cost growth:

- Are programs to develop completely new systems more prone to cost growth than programs to modify existing systems?
- Are "crash" programs inherently more susceptible to cost growth? Does concurrency (simultaneous or overlapping development and production) necessarily doom a program to high cost growth?
- How much does adherence to the planned production schedule influence cost growth in production? Do programs whose procurement is stretched out have higher costs?

We focused on cost and schedule growth in two major product categories, tactical missiles and tactical aircraft. Tactical missiles are particularly prone to cost and schedule difficulties, as prior IDA research has shown [2, 4, and 5]. Tactical missiles, while technologically complex, are viewed as being less "glamorous" than tactical aircraft, and missile programs often do not receive priority. Tactical aircraft are among the most technologically complex products the military buys. They are developed on a custom basis, usually pushing the state of the art. Tactical aircraft development is constrained by size and weight restrictions, and is spurred toward ever-faster goals for operating speeds.

Moreover, the physical environment in which these aircraft operate often involves extreme temperatures, high vibration, and G-forces [6].

We developed both qualitative and quantitative relationships between cost and schedule in missile programs. In addition, we developed quantitative cost/schedule relationships for a small sample of tactical aircraft.

C. ORGANIZATION OF THIS REPORT

Chapter II of this report discusses the data used, including definitions of the key program outcome measures, and includes tables of the basic data. Chapter III discusses detailed reasons for cost and schedule growth, based on case analyses of 15 missile programs. Chapter IV provides quantitative relationships between cost growth and schedule growth. Chapter V summarizes conclusions from the qualitative and quantitative analyses and discusses the implications for DoD.

II. DATA

A. INTRODUCTION

For this study, IDA examined twenty tactical missiles and seven tactical aircraft. Among them were programs classified as major systems. None of the programs in our sample were canceled. The data on these systems were obtained from Selected Acquisition Reports (SARs), from historical memoranda to support DoD program reviews, and from summaries of program data [7 and 8]. Data were current as of the 1992 SARs.

We examined only the first version of each system and not subsequent modifications, unless they were considered as separate programs. DoD treatment of modification programs in its reporting and review process has not always been uniform. Sometimes, as in the case of the F-14, a new version was treated as a new program and went through a new set of reviews and had separate documentation. Other times, as in the case of the F-15, DoD treated the program as one, despite the technical differences between the F-15A/B and the F-15E. When a data source included costs for modified versions, we used data on production schedules to obtain the actual costs for the first version.

B. MEASUREMENT OF COST AND SCHEDULE GROWTH

Major weapon system programs undergo systematic reviews at key points in the process. These so-called milestone reviews are designed to measure the program's progress against its goals in all phases of the process. The major phases are:

- Phase 0: Concept Exploration and Definition
- Phase I: Demonstration and Validation
- Phase II: Engineering and Manufacturing Development
- Phase III: Production and Deployment
- Phase IV: Operations and Support

An expert panel, the Defense Acquisition Board (DAB), judges each program's progress relative to the exit criteria for each phase and issues decisions about the future course of each program. The board is chaired by the Under Secretary of Defense

(Acquisition and Technology). This panel was formerly called the Defense Systems Acquisition Review Council (DSARC).

Figure II-1 provides a schematic of the milestone process. At Milestone II, the government describes the system and makes baseline estimates of cost and schedule. If the system receives DAB approval, it moves into engineering and manufacturing development. (For much of the time represented by this study, this phase was called full-scale development or FSD.) The cost and schedule estimates are updated annually to reflect experience and greater knowledge about the system.

We examined cost and schedule growth by comparing actual outcomes with those planned at the Milestone II review, when the commitment for engineering and manufacturing development was made. Outcomes were expressed as a ratio of actual to planned cost or schedule.

The development cost growth (DCG) ratio is defined as:

$$\mathrm{DCG} = \mathrm{ADC} \div \mathrm{PDC},$$

where

ADC = actual development cost, the actual cost to develop the system, measured in millions of FY 1994 dollars from Milestone II to the end of development of the first version; and

PDC = planned development cost, the planned cost to develop the system, measured in millions of FY 1994 dollars from Milestone II to the end of development of the first version.

The production cost growth (PCG) ratio is defined as:

$$\mathrm{PCG} = \mathrm{APC} \div \mathrm{PPC},$$

where

APC = actual production cost, the actual cost to produce the planned quantity of the system, measured in millions of FY 1994 dollars; and

PPC = planned production cost; the planned cost at Milestone II to produce the planned quantity of the system, measured in millions of FY 1994 dollars.

If the actual quantity produced was greater than that planned at Milestone II, the numerator was the cost to produce only the planned quantity. If the actual quantity was less than that

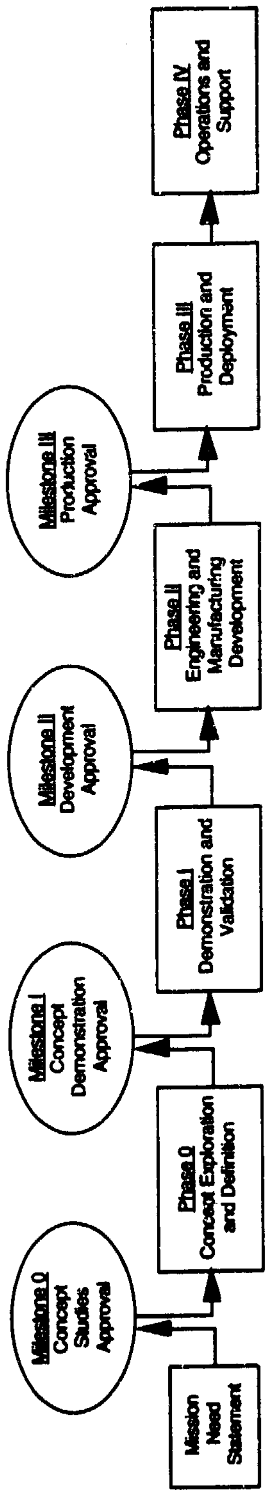

Figure II-1. Acquisition Milestone Process

planned, we used a price-improvement curve to project the cost of producing the planned quantity. In every case, we included data only on actual costs. We did not use DoD future planned costs to measure cost growth.

The total program cost growth (TPCG) ratio is defined as:

$$TPCG = (ADC + APC) + (PDC + PPC).$$

Schedule measures were calculated similarly. The development schedule growth (DSG) ratio is defined as:

$$DSG = ADS + PDS,$$

where

ADS = actual development schedule, actual time to develop the first version of the system, measured in months from Milestone II to initial operational capability (IOC); and

PDS = planned development schedule, planned time to develop the first version of the system, measured in months from Milestone II to IOC.

The production schedule stretch (PSS) ratio is defined as:

$$PSS = APS + PPS,$$

where

APS = actual production schedule, actual time to produce the planned quantity of the system, measured in months from Milestone III to the end of production of the planned quantity; and

PPS = planned production schedule, planned time to produce the planned quantity of the system, measured in months from Milestone III to the end of production of the planned quantity.

The timing of production is based on obligation of funds, not deliveries, because that is the way the plans are made. If the planned quantity has not yet been produced, a linear projection was made based on actuals.

Total schedule growth (TSG) ratio is defined as follows:

$$TSG = (ADS+APS) + (PDS+PPS).$$

TPCG and TSG may be useful in understanding the effect of development disruptions or successes on the total program. For example, we may observe that a program completed development seriously behind schedule, but within its planned cost. While it is possible at that juncture to have a production program proceed as planned, it is also possible that issues of performance, producibility, or maintainability are not completely resolved until after production is underway, adding to production costs.

The definitions of cost and schedule growth in this paper differ from those in past IDA studies [2 and 5]. In those studies, we included all development spending in our cost growth measure, while in the current study, we used only spending past Milestone II. Production schedule stretch is a new measure that captures the time to produce the planned quantity. These revisions provide measures that are appropriate to the issues raised in the current study.

C. TACTICAL MISSILES

Table II-1 presents schedule data for the sample of twenty tactical missiles, and Table II-2 presents cost and schedule growth measures. As seen in Table II-1, the programs for which information could be obtained represent a span of twenty years, with FSD start dates ranging from 1962 to 1982. The sample includes tactical missiles from the three services and includes both air-launched and surface-launched missiles.

D. TACTICAL AIRCRAFT

Table II-3 presents schedule data for the sample of seven tactical aircraft, and Table II-4 presents cost and schedule growth measures. The sample included the major fighter aircraft programs over the past three decades. The F-14D was omitted, because its experience was much more limited than the others, and in 1992, it was on the verge of cancellation.

Table II-1. Schedule Data for Tactical Missiles

Missile	Milestone II		IOC		Development Schedule (number of months)		Milestone III		Production End		Production Schedule (number of months)	
	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual
Phoenix AIM-54A	Dec-62	Dec-62	Dec-68	Dec-73	69	134	Sep-70	Nov-70	Sep-79	Feb-80	108	111
AMRAAM	Sep-82	Sep-82	Aug-86	Sep-91	48	110	Feb-84	Jun-87	Sep-94	May-16	127	347
Hellfire	Feb-76	Feb-76	May-83	Jul-86	88	127	Feb-80	Nov-81	Sep-86	Apr-88	79	78
HARM	Feb-78	Feb-78	Sep-81	Nov-83	44	70	Sep-81	Sep-83	Sep-87	Aug-90	72	84
Sparrow AIM-7F	May-65	Dec-65	Jan-69	Apr-76	45	126	Jan-68	Oct-74	Sep-73	Jan-79	68	51
TOW	Apr-63	Apr-63	May-68	Sep-70	62	90	Aug-66	Nov-68	Sep-72	Aug-92	73	285
Sidewinder AIM-9L	Jun-71	Aug-71	Mar-74	May-78	33	82	Apr-74	Apr-76	Sep-77	Feb-84	41	94
TOW 2	Sep-78	Sep-78	Sep-83	Sep-83	61	61	Sep-81	Sep-81	Sep-90	Sep-90	108	110
Harpoon	Jun-73	Jun-73	Jun-76	Jul-77	37	50	Jun-74	Jul-74	Sep-81	May-86	87	144
Maverick AGM-65D/G	Sep-76	Sep-76	Jun-81	Feb-86	58	115	Jun-79	Mar-82	Sep-85	Apr-94	75	145
Sparrow AIM-7M	Apr-78	Apr-78	Jun-81	Jan-83	39	58	Jun-81	Nov-82	Sep-85	May-87	51	55
Sidewinder AIM-9M	Feb-76	Feb-76	Aug-82	Sep-82	79	80	Dec-80	Feb-81	Sep-85	Mar-84	57	37
Phoenix AIM-54C	Oct-76	Oct-76	Oct-83	Dec-86	85	124	Jul-79	Dec-79	Sep-86	Mar-85	86	64
Improved Hawk	Nov-64	Nov-64	Apr-71	Nov-72	78	97	Apr-69	Jun-69	Sep-75	Aug-82	77	160
Shillelagh	Jun-59	Jun-59	Jan-67	Jun-67	92	97	Nov-64	Nov-64	Jun-69	May-72	55	90
Pershing II	Feb-79	Feb-79	Dec-84	Dec-83	71	59	Oct-83	Jun-82	Sep-86	Aug-87	35	62
Patriot	Mar-72	Mar-72	Apr-82	Jun-83	123	137	Apr-79	Sep-80	Sep-89	Mar-03	125	270
Lance	May-67	Dec-67	Jun-70	Jun-72	38	55	Jan-69	Jan-71	Sep-73	Jun-75	56	53
Maverick AGM-65A	Jul-68	Jul-68	Dec-71	Feb-73	42	56	Jul-71	Jul-71	Sep-78	Jul-78	86	84
MLRS	Jan-77	Jan-77	Nov-82	Mar-83	71	75	May-80	May-80	Sep-88	Mar-89	100	106
Median					61.5	86					76	92

Table II-2. Cost and Schedule Growth Measures for Tactical Missiles

	Development		Production		Total Program	
Missile	Cost Growth	Schedule Growth	Cost Growth	Schedule Stretch	Cost Growth	Schedule Stretch
Phoenix AIM-54A	1.54	1.94	1.35	1.03	1.38	1.38
AMRAAM	1.76	2.29	1.84	2.73	1.84	2.61
Hellfire	1.22	1.44	1.60	0.99	1.46	1.23
HARM	1.61	1.59	1.51	1.17	1.52	1.33
Sparrow AIM-7F	4.26	2.80	1.58	0.75	1.73	1.57
TOW	1.20	1.45	1.78	3.90	1.71	2.78
Sidewinder AIM-9L	4.89	2.48	2.07	2.29	2.23	2.38
TOW 2	1.39	1.00	0.95	1.02	0.97	1.01
Harpoon	0.90	1.35	1.85	1.66	1.66	1.56
Maverick AGM-65D/G	1.07	1.98	1.45	1.93	1.42	1.95
Sparrow AIM-7M	0.96	1.49	2.04	1.08	2.00	1.26
Sidewinder AIM-9M	2.04	1.01	1.02	0.65	1.10	0.86
Phoenix AIM-54C	1.67	1.46	1.93	0.74	1.89	1.10
Improved Hawk	1.16	1.24	1.63	2.08	1.56	1.66
Shillelagh	1.31	1.05	1.54	1.64	1.47	1.27
Pershing II	1.13	0.83	2.31	1.77	1.84	1.14
Patriot	1.62	1.11	1.79	2.16	1.74	1.64
Lance	1.08	1.45	1.20	0.95	1.13	1.15
Maverick AGM-65A	1.04	1.33	0.99	0.98	1.01	1.09
MLRS	1.02	1.06	0.88	1.06	0.90	1.06
Median	1.26	1.45	1.59	1.12	1.54	1.30

Table II-3. Schedule Data for Tactical Aircraft

Aircraft	Milestone II		IOC		Development Schedule (number of months)		Milestone III		Production End		Production Schedule (number of months)	
	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual	Planned	Actual
F-5E	Dec-72	Aug-72	Jun-74	Mar-74	18	19	Mar-73	Jul-73	Sep-75	Apr-75	30	21
AV-8B	Jun-79	Jul-79	Jun-85	Aug-85	72	74	Apr-82	Apr-82	Sep-88	Sep-94	77	149
F-16	Mar-75	Apr-75	Aug-78	Aug-78	41	41	Jan-77	Jan-77	Aug-81	Feb-82	53	61
F-14A	Feb-69	Feb-69	Apr-73	Dec-73	50	59	Mar-71	Dec-70	Sep-76	May-82	66	137
F-15A/B	Jan-70	Jan-70	Jul-75	Sep-75	66	69	Oct-72	Oct-72	Sep-79	Sep-80	83	95
A-10	Jan-73	Jan-73	Jun-77	Oct-77	53	58	May-74	Jul-74	Sep-79	Oct-83	64	111
F/A-18	Jan-76	Jan-76	Sep-82	Mar-83	80	87	Nov-78	Nov-78	Sep-88	May-90	118	138
Median					53	59					66	111

Table II-4. Cost and Schedule Growth Measures for Tactical Aircraft

Aircraft	Development		Production		Total Program	
	Cost Growth	Schedule Growth	Cost Growth	Schedule Stretch	Cost Growth	Schedule Stretch
F-5E	1.05	1.06	0.79	0.70	0.91	0.83
AV-8B	1.40	1.03	0.93	1.94	0.98	1.50
F-16	1.20	1.00	1.08	1.11	1.11	1.06
F-14A	1.53	1.18	1.17	2.08	1.26	1.69
F-15A/B	1.08	1.05	1.19	1.14	1.20	1.10
A-10	1.37	1.09	1.34	1.73	1.37	1.44
F/A-18	1.15	1.09	1.42	1.17	1.40	1.14
Median	1.20	1.06	1.17	1.17	1.20	1.14

III. REASONS FOR COST AND SCHEDULE GROWTH

A. INTRODUCTION

In this chapter, we discuss the reasons for cost and schedule growth in the program areas we selected. We do this by examining the lessons learned from experiences with past weapon programs. The emphasis is on tactical missiles, because that is the area of greatest cost and schedule variation. We were able to analyze several of the tactical missile programs, and we discuss which factors were most important in determining their outcomes. In the final section of this chapter, we explore reasons for variations in cost and schedule growth among the tactical aircraft.

B. LESSONS LEARNED FROM MISSILE PROGRAMS

This section highlights the reasons for cost and schedule growth in selected tactical missile programs by presenting case studies of various programs included in our study. The systems discussed here were chosen on the basis of information availability and do not represent a scientific sample. They do, however, include instances of programs with very high and very low cost and schedule growth. Among the sources used in compiling this information were References [4] and [9].

At the beginning of each program discussion, a chart similar to Figure III-1 is presented to indicate the position of the program's outcome measures relative to the rest of the tactical missiles. The solid lines span the ranges of the outcome measures, from minimum to maximum. The tick marks on the lines represent the median of the outcome measures, and the black dots show the outcome measures for the particular system being depicted. Such a chart allows us to see, for example, that the AIM-7F's development cost and schedule growth were well above the medians for the tactical missiles in our study. Figure III-2 provides similar data for the AIM-7M.

1. Sparrow Missile Modifications (AIM-7F and AIM-7M)

The Sparrow missile is a relatively large medium-range air-to-air missile that uses semi-active radar guidance. The Sparrow has been successfully modified several times to

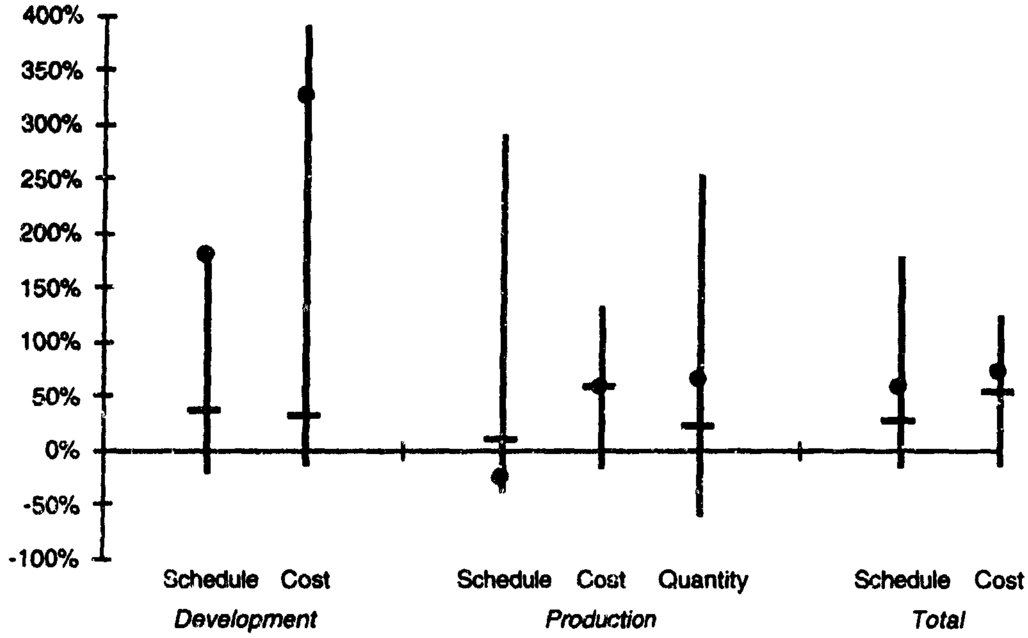

Figure III-1. Outcome for the Sparrow AIM-7F

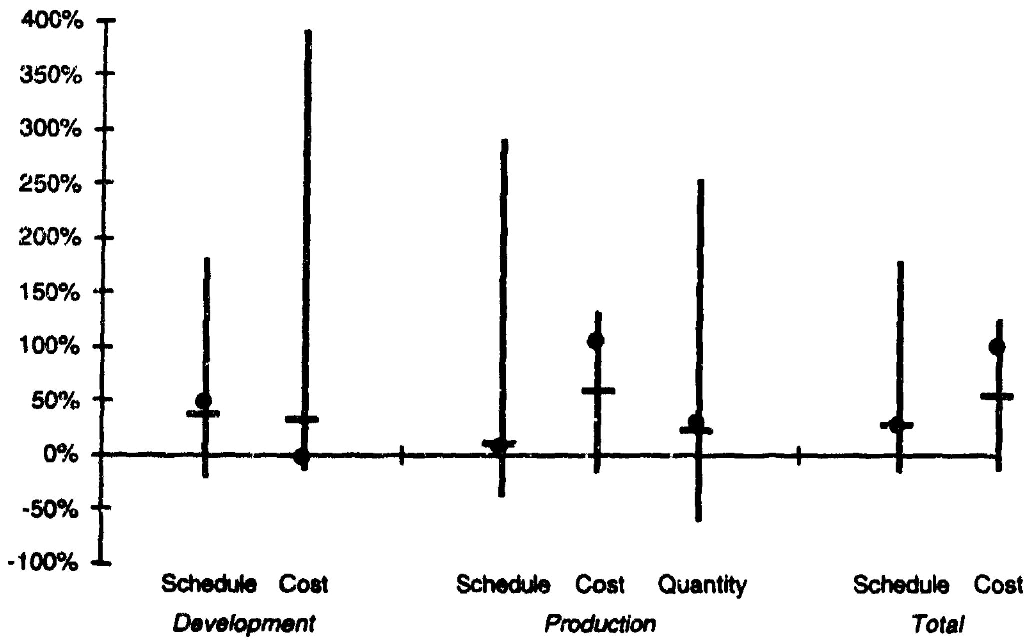

Figure III-2. Outcome for the Sparrow AIM-7M

counter a changing threat. These modifications to the original AIM-7C and D versions are largely evolutionary, making improvements in reliability, range, lethality, and clutter rejection. The Sparrow has been used in combat.

Sparrow was a joint-service program; the Navy served as the lead service and the Air Force supported. The Raytheon Company has been the prime contractor for all versions, while General Dynamics Corporation has been the second source for the AIM-7F and the AIM-7M.

Planners in the early stages of the modifications considered them to be technically challenging, but well-understood. However, in both cases (as well as in the case of the earlier AIM-7E), the modifications involved the guidance and control section, the most technologically complex section of the missile. The AIM-7F had very high development cost growth of 326 percent. The schedule slipped almost seven years, and the system took almost three times as long as originally planned from Milestone II to IOC. If modification programs are complex, they can be as difficult to develop as all-new systems. However, the later modification, the AIM-7M, was relatively simple, and development cost growth was low.

The AIM-7F modification incorporated a switch to a pulse-Doppler seeker and a new government-furnished fuze. The differences between the AIM-7E and the AIM-7F included a move from vacuum tube circuits in the guidance section to solid-state circuits, a larger rocket motor, and a larger warhead. The technology risk was underestimated. The technical problems necessitated several redesign efforts, delays in flight testing, and more launches of test missiles. Technical difficulties were apparent during flight tests. After seven launches, a major redesign effort was initiated, which resulted in a 13-month gap between contractor demonstration test and Navy technical evaluation.

The technical evaluation (TECHEVAL) and operational evaluation (OPEVAL) for the AIM-7F was extended because of the technical problems of incorporating the seeker into the missile. A second OPEVAL involving 25 missile launches was conducted. An unusually large number of pre-production missiles were built and tested, and the test program consisted of 99 launches. IOC was seven years later than planned.

The Navy decided on dual-source production of the AIM-7F in early 1971, toward the end of engineering development. The Navy was concerned about the performance of the system. Annual competitions were held from 1977 through 1980. Raytheon won the larger shares of the buys three out of four times.

The AIM-7M program included a competitive prototype phase to select between the Raytheon and the General Dynamics seeker designs. Raytheon was selected. The AIM-7M program had a high launch rate relative to other air-to-air programs. The lack of technical problems in the AIM-7M resulted in its relatively easy development schedule [9].

Competition did not seem to have much effect on the costs for AIM-7F and AIM-7M, even though both had competitive sourcing of the missile and major subsystems. The monopulse seeker in the AIM-7M was developed by Raytheon, in competition with General Dynamics. In the AIM-7F, any savings from competition were overwhelmed by the technical difficulties. The AIM-7F program acquired more quantity than planned over a longer time than planned. Thus, it is not clear whether the favorable production cost growth outcome was due to the competition or to program stability. The government was, however, pleased with the non-cost aspects of the competition, including better government control and more efficient production methods.

The low development cost growth of the AIM-7M was probably due to the more modest technical goals rather than to competition. However, the program had high production cost growth, despite only modest rate fluctuations. The AIM-7M had higher total program cost growth than the AIM-7F.

The political environment does not appear to have been a major factor in any of the modifications. There were some minor cost and schedule problems due to lack of funding and reduction of quantities in the AIM-7E and AIM-7F programs. More recently, the services have withdrawn funds from the AIM-7M to support the newer Advanced Medium-Range Air-to-Air Missile (AMRAAM), and this may have caused problems with production in the AIM-7M.

2. Sidewinder Missile Modifications (AIM-9L and AIM-9M)

Both the Sidewinder AIM-9L and AIM-9M modification programs encountered major problems in development, as evidenced by large development cost and schedule growth. Sidewinders are short-range air-to-air missiles, the later versions of which used infrared guidance.

Development of the original Sidewinder began in 1950, and the missile became operational in 1956 (designated as the AIM-9B) for the Navy and the Air Force. Over 60,000 AIM-9B missiles were produced by Philco Corporation (now Ford Aerospace Corporation) and General Electric Company.

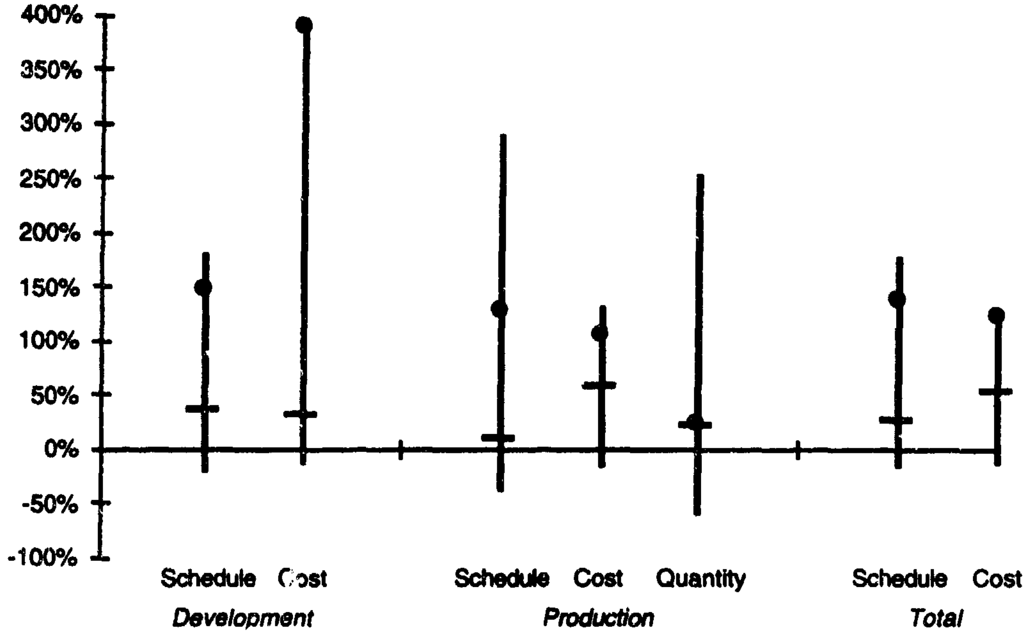

Figure III-3. Outcome for the Sidewinder AIM-9L

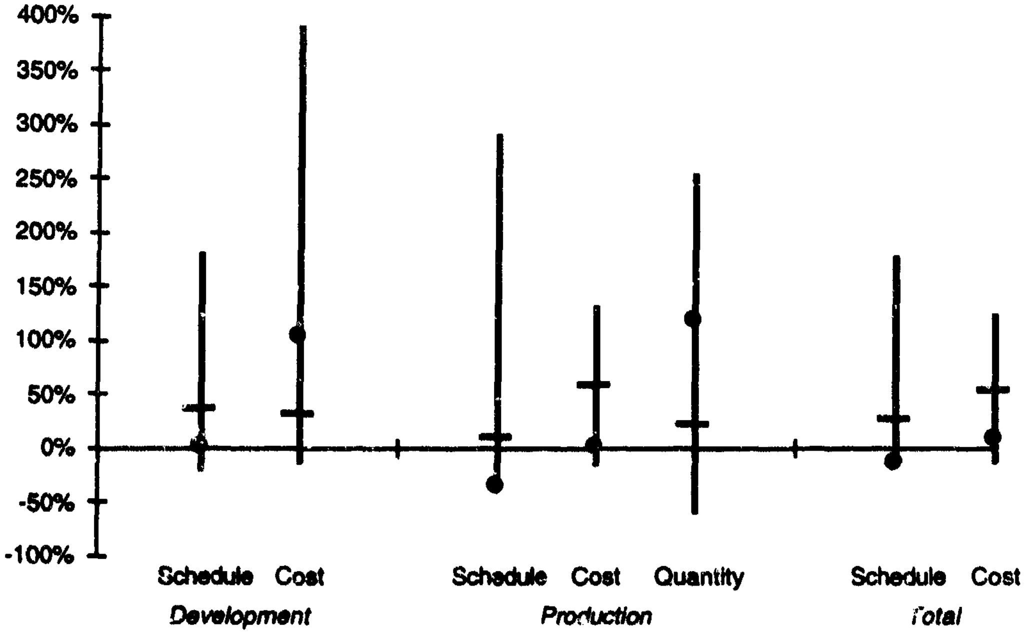

Figure III-4. Outcome for the Sidewinder AIM-9M

Several other modifications took place before the development of the AIM-9L and AIM-9M:

- The Navy and the Air Force pursued separate modifications of the AIM-9B. The Navy AIM-9C was a semiactive radar homing variant that was never fully developed. It was eventually withdrawn in favor of the AIM-9D, which had an improved seeker, an improved motor, and a continuous-rod warhead.
- As a result of the Navy's changes to the AIM-9B, the Air Force hired Philco to change the reference coils back to previous values and to make other improvements. The modified missile, designated the AIM-9E, failed acceptance tests. The contractor offered a bargain price, and the Air Force bought the AIM-9Es and warehoused them. Moreover, a factory was set up in Korea to convert the rest of the AIM-9Bs into AIM-9Es for the Korean armed forces, despite the missiles' test failures. Members of the Israeli armed forces eventually used the missiles, but the Israelis may have made some of their own modifications.
- The Army modified the AIM-9D into a ground-launched version called the MIM-72 Chaparral.
- The Navy added Sidewinder Expanded Acquisition Capability to the AIM-9D to get the AIM-9G, which was produced by Raytheon until 1970.
- The AIM-9H expanded on the AIM-9G by adding solid-state circuitry.
- The Air Force improved the AIM-9E by incorporating solid-state circuitry, improved guidance and control units, and a proximity fuze. The new version was designated AIM-9J.
- The German Air Force incorporated its Viper missile technology into Sidewinder. As a result, Germany agreed to use the AIM-9L as its primary air combat missile and to end the Viper development program.

The AIM-9L began in 1970 when Deputy Secretary of Defense David Packard directed the Navy and the Air Force to join forces in development, according to a preliminary set of design guidelines outlined by IDA. However, the developer (China Lake) ran out of money before the specified design could be completed. Moreover, there were two different versions of the AIM-9L. The Navy version drew cryogen from a launcher-mounted bottle, while the Air Force version carried an internal cryogen bottle.

The two modifications we examine here—AIM-9L and AIM-9M—have new seekers capable of acquiring and locking onto a target even in frontal aspect attack. Earlier versions required stern chase before lock-on [4, Volume II, p. II-1]. In both cases, the fundamental mistake made was to view the modifications as interim products, stepping stones to the next-generation system. This mistaken view produced an aggressive acquisition strategy, one that was doomed to failure. The acquisition strategies for the AIM-9L and AIM-9M both included:

- few development test articles
- use of a single contractor
- substantial concurrency (overlap) between the development test period and production.

In the case of the AIM-9L, the most important modifications were to the seeker head. Initial testing failures made it impossible to keep to the original schedule. In addition, there were technical problems during assembly of the first engineering unit. Aimpoint shift was also a severe problem. Instead of the 33 months planned, development of the AIM-9L (Milestone II to IOC) lasted over twice as long. Instead of a minimal 30 development articles, 192 were needed. The AIM-9L program followed a fly-before-buy acquisition strategy.

During preparation for the Milestone III review of the AIM-9L, it was realized that the design-to-cost goal could not be met, but that unit costs for the production missiles would be at least 42 percent higher than originally estimated. At this point, the program was drastically restructured to allow sufficient time and funding for strict adherence to the "fly-before-buy" concept. It was decided to take an extra five months to bring on a second-source contractor and to add enough test missiles to make sure the system worked properly. This resulted in a 389-percent increase in development costs. Moreover, production began two years late, and IOC was four years late. The technical problems and the restructuring of the program also resulted in high (107 percent) production cost growth.

The AIM-9M was later instituted to fulfill the original plan for the AIM-9L, which called for countermeasure rejection. That feature was eliminated from the AIM-9L plan when it was clear that the program was over-running its costs. Moreover, the guidance section was repackaged to accommodate a 20- to 25-percent increase in complexity and to improve producibility. Dual sources for all major assemblies and firm-fixed-price production contracts were used. While development was basically completed on time, there was high development cost growth. However, unlike the experience of the AIM-9L, the development problems of the AIM-9M did not spill over into production. A difference of the AIM-9M production process is that the subassemblies that make up the missile were shipped to Navy and Air Force facilities where the missile was assembled.

From the available data, it is impossible to determine whether or not funding shortages adversely affected the ability of the programs to meet cost and schedule goals.

Schedule delays in the AIM-9L program were clearly due to early failures in testing. These failures prompted OSD to slow down the program and not allow it to leave development until problems were resolved. The results of both the AIM-9L and AIM-9M programs show the pitfalls in underestimating the technical difficulty of modifications to guidance and control systems, even when the airframes remain essentially unchanged.

Unlike the AIM-9L, the AIM-9M completed development essentially on time after 80 months. By February 1976, when the development plan for the M version was finalized, program officials knew that the 33-month schedule for the L was a gross underestimate, and more time was allowed for the M. The L version was eventually finished in 82 months, only two months longer than the M version, but double its original estimate.

A major difference between the L version and the M version was production rate relative to plan. For the AIM-9L, the restructuring of the program meant that the first 9,258 missiles, planned to take 41 months, took 94 months to complete. By contrast, the government planned to produce 7,450 AIM-9M missiles in 57 months and actually produced them 20 months sooner. The accelerated production rate was partly due to foreign military sales. The technical problems in the L version's development, the unrealistic development schedule plan, and the slow production schedule combined to result in a system that cost more than twice as much as planned overall. The M version had a more conservative development schedule. It still ran into development cost problems, although not as severe as those of the L version. Overall, the accelerated production schedule, as well as a vigorous foreign military sales program, resulted in low total cost growth for the M version.

3. Phoenix Missile (AIM-54A and AIM-54C)

The Phoenix missile has two versions—the AIM-54A, which was a new concept that did not replace any existing system, and the AIM-54C, an improvement of the original Phoenix that changed components from analog to digital.

The Navy devised a requirement in the 1950s and initially pursued it with the AAM-M-10 Eagle air-to-air missile, which was canceled in 1961. In the 1960s, Hughes Aircraft Company developed the TFX missile for use on the F-111B aircraft, and it was this missile that became the Phoenix A. When the F-111B was replaced, the Phoenix was adapted for use on the successor aircraft, the F-14.

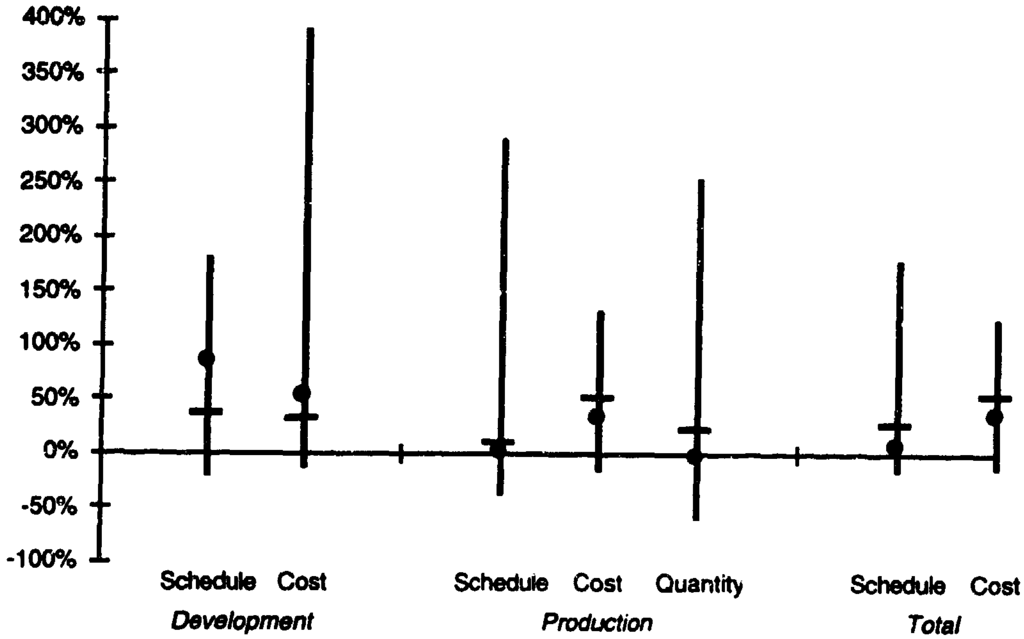

Figure III-5. Outcome for the Phoenix AIM-54A

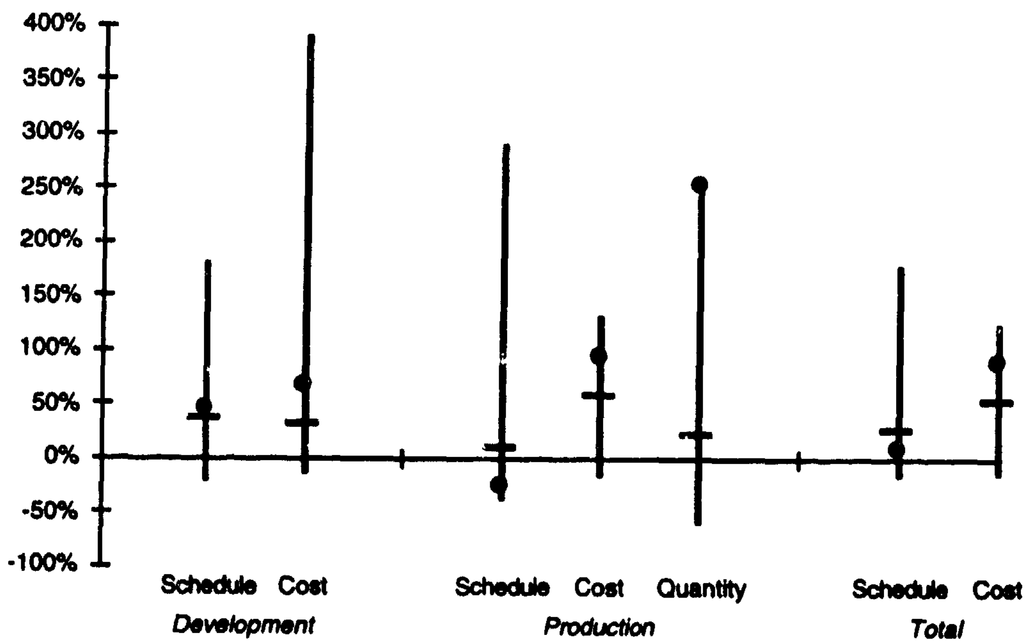

Figure III-6. Outcome for the Phoenix AIM-54C

The AIM-54A began development in 1962 and reached IOC in December 1973. IOC was later than planned, partly due to problems with the aircraft platforms—e.g., the cancellation of the F-111B and schedule delays in the F-14. There was a 20-month delay in approval of the missile for service, largely due to delays in testing. The testing delays were due to unavailability of test platforms and late deliveries of the pilot production missiles.

Development cost growth for the AIM-54A was 54 percent, and the number of test articles was cut in order to contain development costs. However, production cost growth for the Phoenix A was only 30 percent, less than the average for new tactical missile programs. Reasons cited for cost growth in production include underestimation of the technology risk, delays in the test schedule, and engineering changes [4]. It is also notable that Hughes never faced any competition from the advanced development phase on.

The AIM-54C experienced substantial problems in both development and production. The development of the AIM-54C improvements began in February 1976, and Milestone II was reached October 1976. There was considerable concurrency between development and production. The build-up to full-rate production was slow: the first three production lots contained fewer than 100 missiles. IOC was in December 1986, more than three years later than planned, representing a 45-percent development schedule slip.

Development costs were 67 percent higher than planned, and 50 percent more development articles were required. Reasons for the development problems include:

- engineering changes to the guidance and control section,
- electronic counter-countermeasures (ECCM) engineering changes, and
- rework of the igniter safety mechanisms [4].

Quality problems that occurred from June through November 1984 prompted the Navy to stop accepting deliveries of the missiles until the problems were identified and resolved. In 1984, the Navy began an effort to develop a second source for the Phoenix C. Raytheon Company was selected as the second source, and head-to-head competition between Hughes and Raytheon began in FY 1989. However, production ended with the FY 1990 buy.

The high production cost growth for the AIM-54C is largely due to the development problems spilling over into production. IOC did not occur until the eighth year of production. In addition, it may be that producibility issues were not adequately addressed during development. In the late 1980s, the program was in danger of being canceled so that resources could be devoted to the development of the next-generation system, the Advanced Air-to-Air Missile (AAAM). Moreover, five years were devoted to qualifying a second source, for only two years of head-to-head competition. Even though the system was produced rapidly, the combination of the up-front cost of dual-sourcing and concurrency increased the total cost of the AIM-54C.

4. Advanced Medium-Range Air-to-Air Missile (AMRAAM)

The AMRAAM, a replacement for the Sparrow, provides double the capacity at half the size. It was designed to provide all-weather capability for the F-16 fighter and also to be used on the F-14, F-15, and F-18 aircraft. It is a joint-service program of the Air Force (the lead service) and the Navy. The technical difficulty of the program can be considered to be roughly comparable to the High-Speed Anti-Reduction Missile (HARM), but more difficult than the Phoenix [4]. However, developers initially believed it would be only a little more costly than the F version of the Sparrow.

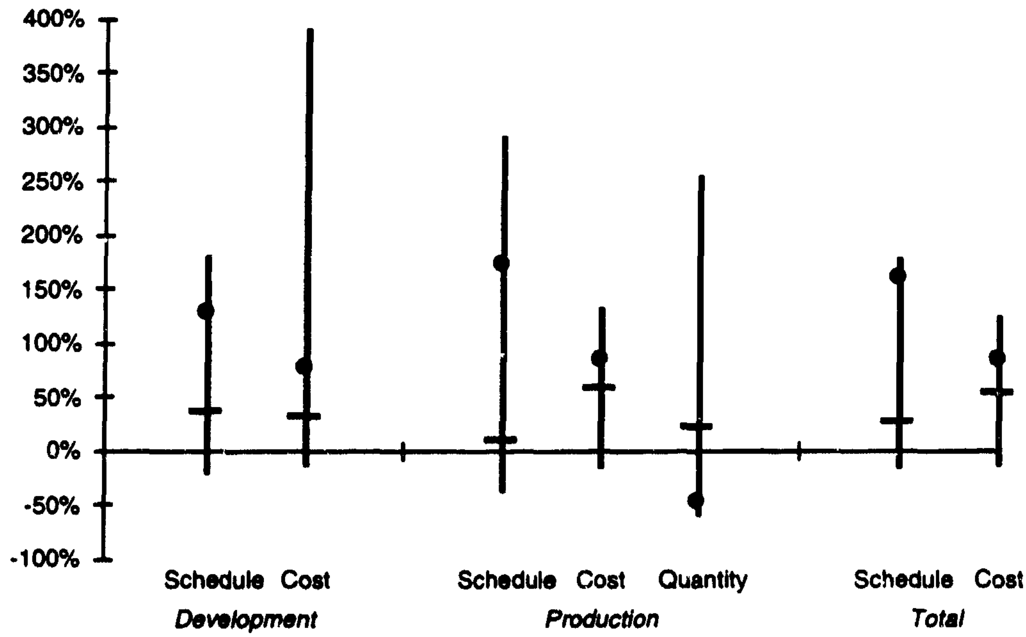

Figure III-7. Outcome for the AMRAAM

The program began in 1977 with concept definition and five contracts for competitive advanced development. Milestone I was in November 1978, and demonstration/validation contracts were awarded to Hughes Aircraft Company and Raytheon Company in February 1979. Five Raytheon and three Hughes missiles were launched. Hughes was selected as the prime contractor in December 1981. The Hughes FSD contract was fixed-price, with priced options for production lots 1 and 2 and an unpriced option for lot 3. Milestone II was September 1982—at that time, Raytheon was selected as the second source.

There was pressure to get AMRAAM fielded quickly to synchronize its arrival with the first F-16s sent to Europe. The program thus inevitably had a high degree of concurrency. Important tasks to demonstrate the performance of the missile were delayed until full-scale development. FSD was planned for a period of 50 months. Long-lead release occurred after only 19 test launches.

By December 1983, it was clear that Hughes could not deliver the FSD articles on time. In addition, a General Accounting Office (GAO) report cited problems of cost growth due to an unrealistic validation phase schedule and an overly ambitious FSD schedule. Technical problems that contributed to the cost and schedule problems in development included problems in developing the guidance and control, problems in missile integration and assembly, and delays in flight testing due to the delivery problems. A management problem that contributed was pressure to make the AMRAAM appear cheaper than its competitor, the AIM-7M Sparrow.

The first launch of the AMRAAM occurred in December 1984. Deliveries of sufficient missiles to fully equip the first operational squadron were completed in early December 1990. Air Force IOC was achieved in September 1991, 62 months later than planned. Six months of the Air Force IOC delay was attributed to the lack of availability of a fully operational F-15 radar computer tape. Navy OPEVAL slipped from March 1992 to December 1992 because of problems with the F/A-18 radar tape, then slipped to August 1993 because of issues identified during the certification process of the radar tape. Phase I of the Air Force follow-on test and evaluation (FOT&E) slipped from March 1992 to February 1993 because of availability of test assets.

In the first head-to-head competition, Hughes Aircraft Company won 59 percent of the FY 1989 buy. In FY 1990, the total quantity was divided evenly between Hughes and Raytheon. In FY 1991/1992, Hughes won a 981-missile buy, while Raytheon received an order for 810. In FY 1993, Hughes again won a larger share, 58 percent of the total. However, in FY 1994, Raytheon was awarded the larger share, 60 percent of the buy.

AMRAAM was deployed in Operation Desert Storm in February 1991. Although it was not fired, significant operational experience was gained, and the missile greatly exceeded the mature MTBMA requirement. The DAB Milestone IIIB review was held in May 1991, and the program was authorized to continue with low-rate production through FY 1992. The program received approval for full-rate production in April 1992. In

December 1992, an Iraqi Air Force MIG fighter was downed under actual combat conditions using an AMRAAM. A second Iraqi MIG was shot down in January 1993.

AMRAAM is a prime example of the tendency to oversell programs. According to a recent case study, "The most important theme to draw from this case is the importance of managing expectations. The chief cause of AMRAAM's woes is that managers vastly oversold the program in terms of cost and schedule" [10].

Substantial production cost growth (59 percent) on AMRAAM went along with the development cost growth. Underestimated technical difficulty, combined with less demonstration/validation testing than originally planned, produced problems in production as well. Concurrency was problematic—the AMRAAM had almost simultaneous development test and evaluation (DT&E) and initial operational test and evaluation (IOT&E). An unrealistic FSD flight test schedule further compounded the problems.

In 1986, Congress capped both the FSD and production programs. FSD was completed within the cost cap, but Congress had to increase the production cost cap twice. Low-rate initial production began in June 1987, more than three years later than planned. The DAB reviewed cost and schedule breaches in December 1989. A drastic cutback in production quantity and a major schedule stretchout resulted in a production schedule stretch of 173 percent for this program. This, combined with dual sourcing at less than full rate, resulted in high production cost growth.

The combination of reduced production quantities and expanded schedules, both exhibited in the AMRAAM program, is a familiar recipe for cost growth; however, the jury is still out on the program. Approval for full-rate production was not given until April 1992. Future buys may be less costly and the final cost growth figure, lower.

5. Maverick Missile (AGM-65A and AGM-65D/G)

The Maverick is an air-to-ground missile with a close air support mission. Two versions of the missile were used for our study, AGM-65A and AGM-65D/G.

The early version of the Maverick used the total package procurement (TPP) concept. The TPP negotiations began in the late 1960s, a time when other TPP programs were having major problems. The contract definition phase was extended about a year to allow intensive negotiations toward the goal of designing "the perfect contract." The original FSD contract contained options for three production buys.

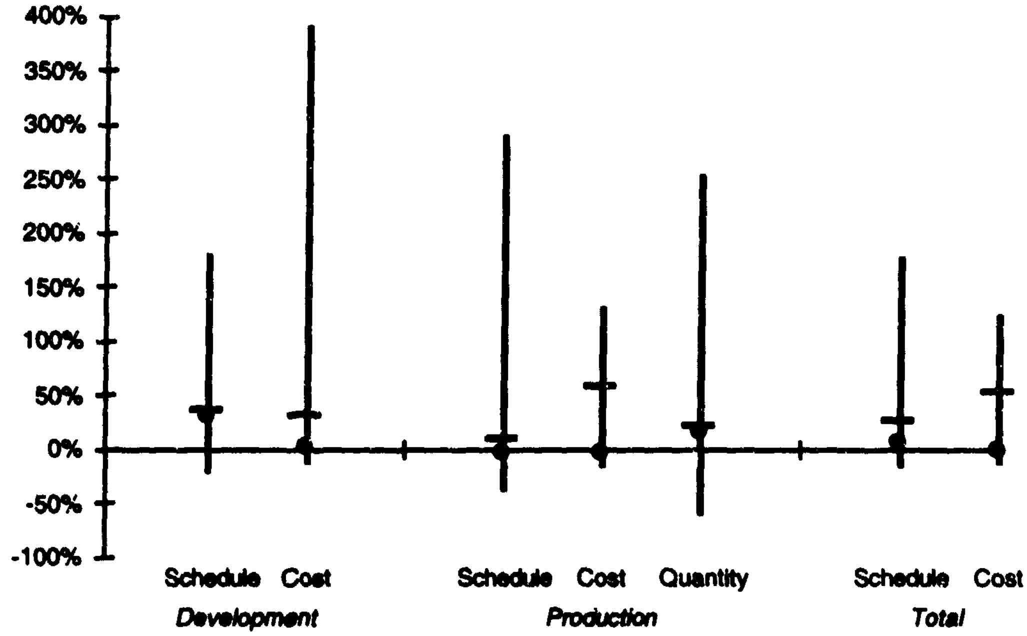

Figure III-8. Outcome for the Maverick AGM-65A

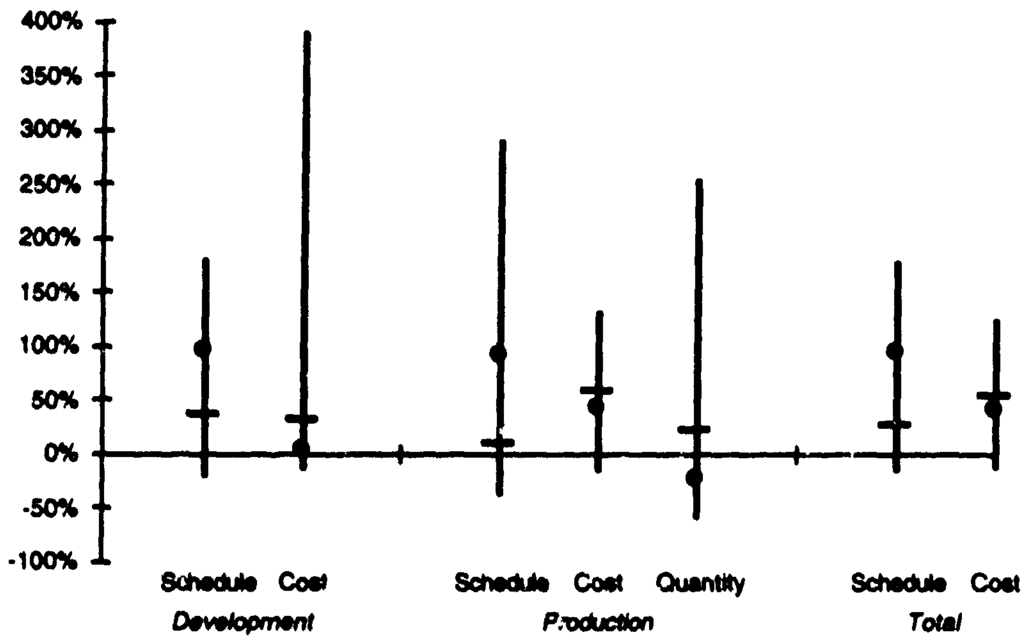

Figure III-9. Outcome for the Maverick AGM-65D/G

The contract included incentives for good performance and penalties for unacceptable performance. For example, a missile hit rate of 90 percent resulted in a $3 million incentive fee. If the hit rate was 80 percent, no bonus was given, and if the hit rate was 70 percent, a $1.5 million penalty was applied. If the hit rate got below 70 percent, the contractor was required to provide free replacement hardware for additional testing. Because the 1970s were a time of high inflation, the contract included an escalation clause [5].

From the contractor's point of view, one of the great advantages of TPP was stability. Once the requirements for test success and cost were defined, the contractor could meet them with a minimum of interference, and without constant contract negotiations and reviews. The contractor also believed that the acceptance and execution of Value Engineering proposals saved money. Value Engineering was a program designed to allow contractors to share in cost savings from efficient operation.

However, despite this use of TPP (which has proven completely unsuccessful in other applications), there was very little concurrency in the program. The first production option was exercised in July 1971, one month before testing was complete. Testing was particularly vigorous, with a launch rate of 5.2 missiles per month during Category II testing. Perhaps this lack of concurrency is why the program did reasonably well, despite TPP. In production, both cost and schedule proceeded essentially according to plan.

The B version of the system had better optics, but it still used daylight television guidance. While the A and B versions had problems in daylight if used improperly, they were never intended for night use. The second Maverick in our study is the Imaging Infrared (IIR) Maverick, which uses infrared guidance and is designed for day/night, all-weather operation.

The IIR Maverick is designated AGM-65D/G in the SAR, but there are other versions as well:

- AGM-65D, the first infrared Maverick;
- AGM-65E, a Navy and Marine Corps version with semiactive laser seeker;
- AGM-65F, a Navy anti-ship version; and
- AGM-65G, a modification of the D version with a bigger warhead.

The IIR Maverick had a prototype program that took 18 months from the start to the first launch of a prototype missile. There was no competitive fly-off. A total of 790 flight-hours of captive testing was completed before the award of the FSD contract. The unusually long period of time between the prototype launch program and the start of FSD was devoted to an extended captive-flight program that included 790 flight hours of tests in various operational environments and producibility and cost studies.

The IIR Maverick had its Milestone II review in September 1976, but engineering development did not start until October 1978 due to an OSD-directed funding cut. (As we will see, this helps to explain the high development schedule growth, but low development cost growth.) The original design intent was to use forward-looking infrared (FLIR) equipment to acquire the target and a correlator to bring the Maverick seeker onto the target. The program manager, fearing that the cost of equipment would kill the program, asserted that no electronics other than a small TV display were required to use IIR Maverick. Early tests were run without other equipment, and serious problems were encountered with target location and target lock-on.

After its Milestone IIIA review in March 1982, the IIR Maverick received a partial release for pilot production. In September 1982, the IIR Maverick received full go-ahead for pilot production. There were problems with operational suitability, although not with operational effectiveness. The Hughes production line shut down from March 1984 to December 1984 to correct quality problems. Full-rate production was not authorized until March 1986. IOC was achieved a month earlier, in February 1986.

Meanwhile, a second-source request for proposals (RFP) was released in 1982, and Raytheon was awarded a second-source contract in May 1983. Modifications and add-ons to the contract raised the price to $76.2 million for 15 missiles. Hughes produced sole source from FY 1982–1986. Hughes won 65.7 percent of the buy during the first year of competition (FY 1987); Raytheon won 63.7 percent of the buy in FY 1988; and Hughes won 59 percent of the buy in FY 1988. In early 1989, the government decided to make future awards on a winner-take-all basis. Through the split buys, the government received considerable data on contractor costs, and with lower planned quantities, it could not afford to support two contractors. Hughes won the entire FY 1990 procurement, and Raytheon won the contract to replace 5,255 missiles used in Desert Storm. These were the last missiles bought.

The program had high development schedule growth. It took almost twice as long to develop the IIR Maverick than planned. The time between Milestone II and Milestone IIIB was 72 months, rather than the planned 42, mostly due to a funding cut that delayed the actual start of engineering development. This delay may have actually contributed to the technical success of the program. It is likely that the Air Force's demands may have outstripped the technical capability of the time. Unusually warm weather in winter 1981 delayed winter site tests for one year. The time between Milestone IIIB and IOC was 41 months, not the 15 months planned. This was largely due to underestimation of the technical difficulty of the program.

The IIR Maverick program exhibited low development cost growth, and its production cost growth was below the median. The number of development test articles was reduced to save money. If they had been increased, some of the producibility problems may have been resolved earlier. Pilot production continued for a considerable time before IOC was achieved, so there was a lot of overlap between development and production. A 1982 GAO report following up on the unit cost report breach stated that the largest single cause of unit cost growth was an increased estimate of guidance unit cost reflecting technical and cost problems in the research and development (R&D) phase. The shutdown of the Hughes production line to resolve quality problems also may have contributed to production cost growth. The quantity planned at Milestone II was never achieved, and there was 93 percent schedule growth.

The results of the dual-sourcing strategy are uncertain. There does appear to be some decrease in unit cost, but it was not clear whether or not the up-front investment would be repaid.

Both versions of the Maverick had very low cost growth as compared with other tactical missiles. The Maverick AGM-65A's low cost growth is especially remarkable in light of the fact that it used a total package procurement strategy. Other programs using this strategy have had very high cost growth. The program used an incentive contract with an inflation escalator clause to cushion the effect of the very high inflation of the time. In addition, the AGM-65A was subjected to considerable testing, and production was not permitted to proceed until tests were essentially complete. In production, the program adhered to its production schedule and procured slightly more quantity than planned.

The IIR Maverick was prototyped and tested before FSD, so more accurate cost estimates could be made at Milestone II. There was a two-year hold in engineering development due to a funding cut. This explains the anomaly of high development schedule growth but low development cost growth. Despite a production rate lower than planned (high PSS), production costs were probably contained through dual sourcing with a buyout at the end of the program.

6. Harpoon Missile (AGM-84)

The Harpoon is an interesting case study, because it was a crash development program. The Navy pushed the program schedule ahead by three years to counter an immediate threat from ships equipped with anti-ship missiles. The result was that the development program was completed faster than other similar systems and within its development cost estimates. However, cost growth in production has been high.

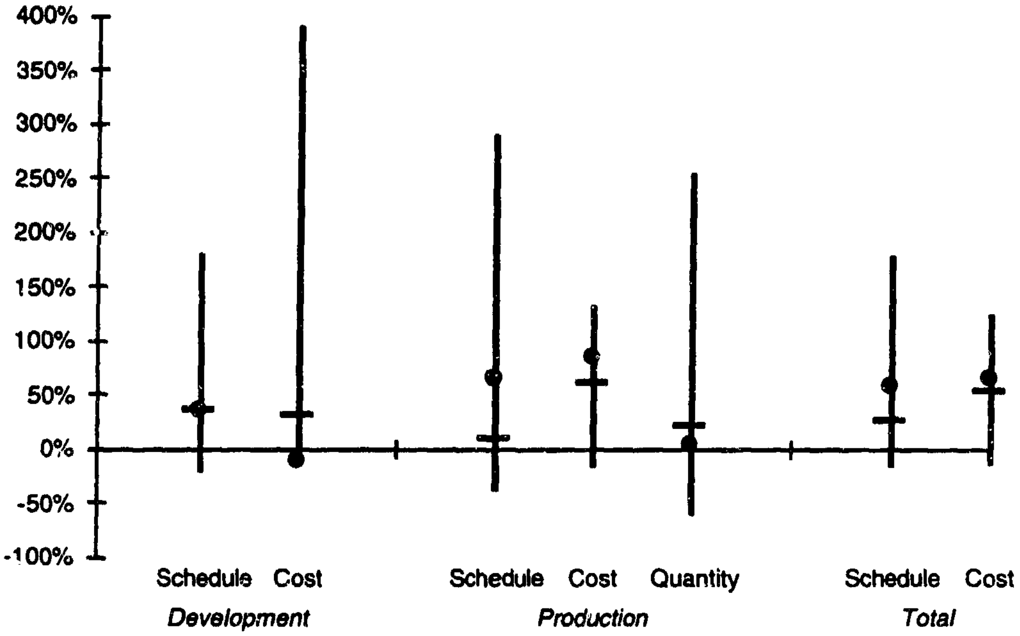

Figure III-10. Outcome for the Harpoon AGM-84

The Harpoon began as an all-weather, air-to-surface, anti-ship missile. The requirement was expanded in 1967 to include a ship-launched variant (RGM-84) and again in 1972 to include a submarine-launched version (UGM-84A). The Harpoon has proven to be excellent in performance and operations.

McDonnell Douglas Corporation had experience in developing concepts for anti-ship missiles. In March 1970, concept development began, and in June 1971, a design contract was awarded after competitive bids. The first flight was in February 1972. Milestone IIA was held in May 1972, and the FSD contract was awarded in June 1973. However, there was no official development estimate until a year later, in the June 1974 SAR. This development estimate of production costs was considerably lower than estimates shown in the SARs both immediately before and immediately after June 1974 (see Figure III-11).

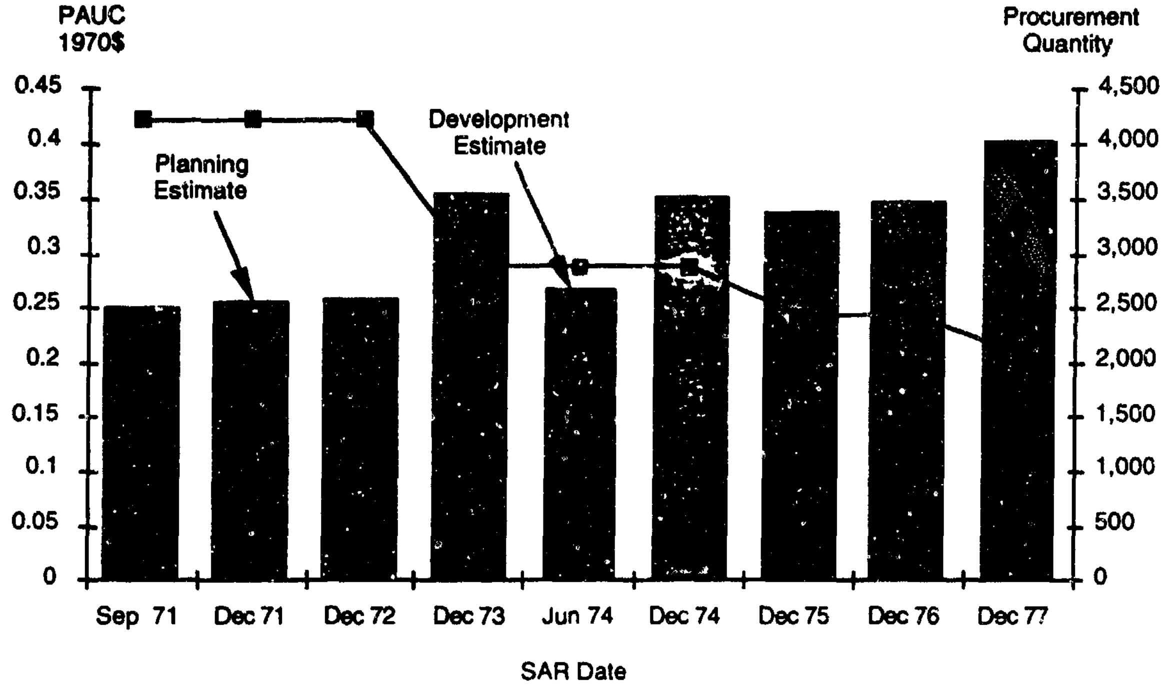

Figure III-11. Estimates of Procurement Average Unit Cost (PAUC) and Procurement Quantity for the Harpoon

The operational evaluation process (from June 1975 to March 1977) uncovered quality problems, which were eventually resolved. As a safeguard against problems due to the rapid nature of development, a comprehensive cost reduction program was activated, and Value Engineering concepts were funded. The first IOC occurred in June 1977, for FF-1052 class ships. There was a high degree of concurrency in the program—initial production go-ahead occurred 7 months before the beginning of Navy technical evaluation. Long-lead release occurred before the start of OPEVAL.

Development thus was considerably faster than typical; the missile was flying less than two years after the beginning of concept development, and IOC was just over five years past Milestone IIA. How was this achieved? Perhaps the program benefitted from McDonnell Douglas's past work in anti-ship missile concepts. In addition, [4] cites the fact that the sustainer engine was made a separate program, and that there was an additional Milestone, IIB, for pilot-line production go-ahead.

Development schedule growth was about average for the group of systems, but the total schedule of 50 months is still much faster than for a typical new tactical munitions. Development cost growth was low, perhaps because of the timing of the development estimate. The large (85 percent) production cost growth could be due to development problems spilling over into production and to production schedule stretchout (it took 66 percent longer than planned to produce the development estimate quantity).

The experience of the Harpoon suggests that development programs can be pushed in critical times, particularly when a single experienced contractor is selected and proven technology is used. However, there is a price to be paid for development haste, and this price often must be paid in production. The crash development program contributed to the difficulty in estimating costs of manufacturing complex subassemblies, the underestimation of rate tooling, the volume of engineering change orders, and high government in-house costs. More prototyping probably would have helped to avoid some of the difficulties in producibility of the seeker and in assembly integration.

7. High-Speed Anti-Radiation Missile (HARM)

The HARM is an air-to-ground missile that was developed jointly by the Navy (lead service) and the Air Force. HARM was developed at the Naval Weapons Center, China Lake, California. It evolved from the Shrike (AGM-45) and the early Anti-Radiation Missiles (AGM-78).

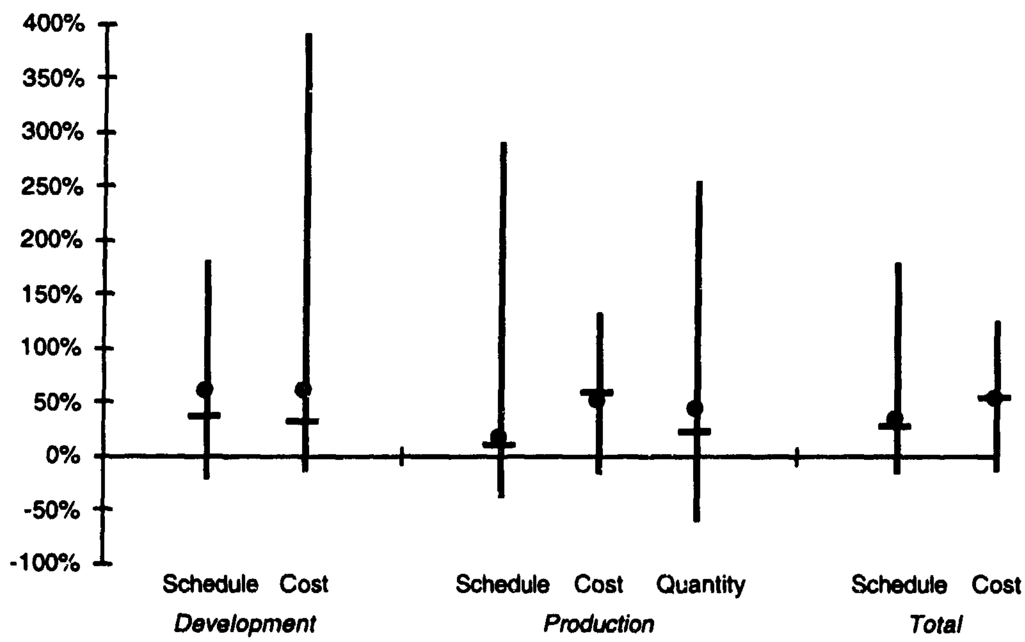

Figure III-12. Outcome for the HARM

Milestone I for HARM was in October 1972, and Texas Instruments, Incorporated, was awarded the contract for integration in May 1974. The first HARM prototype missile, an aerodynamic flight test vehicle, was launched in January 1976. The first prototype guided missile was launched in October 1976. A total of 29 advanced development missiles were tested. Out of 18 prototype firings during engineering development, 13 were complete successes. Corrective actions were taken before procurement funds were committed. At the Milestone II meeting (January 1977), the HARM program was retained in advanced development for: (1) prototyping expanded capability in frequency and aerodynamic maneuverability and (2) conducting a cost-effectiveness analysis of HARM against available alternatives. Just over a year later (February 1978), the program received approval to move into full-scale engineering development. The first launch was in April 1979, and low-rate initial production began in late 1981.

Three other contractors—Ford Aerospace Corporation, Raytheon Company, and Bendix Corporation—took the Texas Instruments hardware and design and developed proposals for manufacturing the system. In December 1982, the Navy threatened to cancel the program unless Texas Instruments substantially reduced program costs. Texas Instruments agreed to several producibility engineering proposals that reduced production costs by around 3 percent and also agreed to provide firm price quotations for two years into the future. The Navy proposed a dual-source plan at Milestone III, but OSD rejected the plan and called instead for vendor-level competition, with the prime contractor responsible for cost control. Competition was never implemented, but Texas Instruments dropped its price substantially, from $937.5 thousand per unit in 1981 to $514.4 thousand per unit in 1982 and $313.8 thousand per unit in 1983. IOC was achieved in November 1983. A total of 40 HARMs were launched in combat against Libya in March and April 1986.

Congress rejected a multiyear procurement strategy for HARM on the grounds that the assumed production rate was more ambitious than was likely to occur, and the potential savings from multiyear procurement were too small. A design-to-cost procurement strategy was used, but the design-to-cost threshold was breached only four years into the program.

Development schedule growth was high compared to other systems in this group, as was development cost growth. Reasons for this included the need for increased funds for A-6E/HARM integration and the expanded capability required. In production, cost growth was slightly below the median for the class. Schedule growth in production was slightly higher than the median. The system exceeded its technical performance requirements.

The requirement for flexible software, while it added to the capability of the system, was difficult to achieve. Because of the technical difficulty of the flexible software requirement, a four-year advanced development phase was planned, but even this was not enough. Prototyping took some extra time, and fixing problems identified added to development costs, but the problems were fixed early. Perhaps as a result, production, where most of the money is, stayed closer to plan than is typical for tactical munitions. Finally, even though the dual-sourcing strategy was rejected, Navy officials have indicated that they believe that the threat of competition led to more reasonable prices from the prime contractor.

8. Hellfire Missile (AGM-114)

The AGM-114 has several distinctive features: it is very light for an air-to-surface missile, it has laser guidance, it is launched from a helicopter (the AH-64), and it is developed by the Army. A comparatively large number of test missiles relative to similar programs were procured and launched.

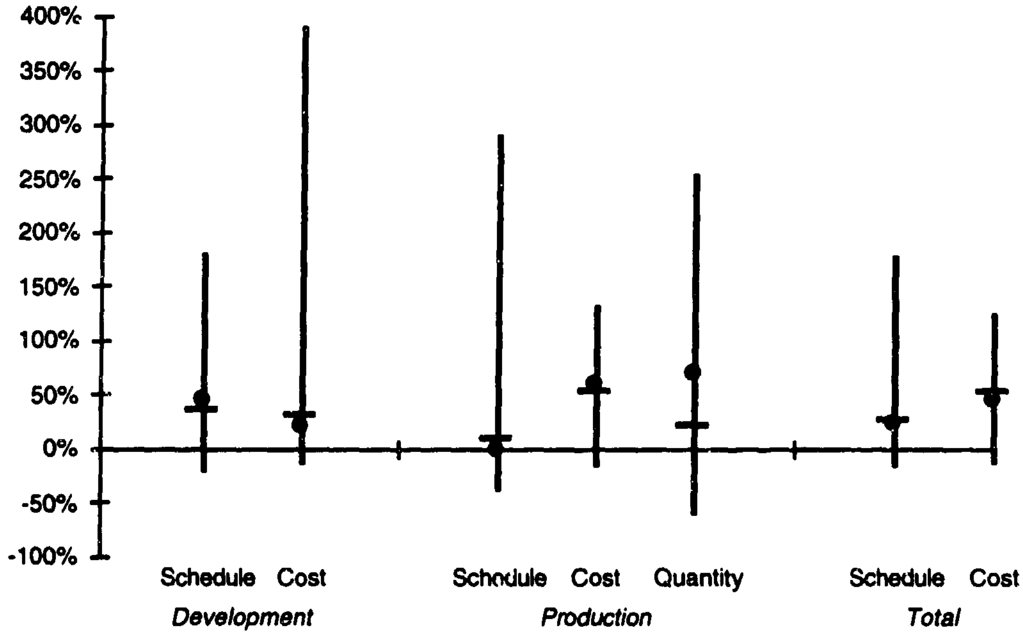

Figure III-13. Outcome for the Hellfire AGM-114

An interesting feature of the Hellfire program is the establishment of a second source at no apparent cost to the government. Up until 1988, according to [4], the net effect of the dual-source capitalization strategy and the pressure of competition was a wash. Prices were essentially the same as if there had been no competition.

The government followed a split-buy strategy in FY 1984-1989. In FY 1990, Rockwell International Corporation won the total quantity for FY 1990, with firm-fixed-price options for FY 1991 and FY 1992. Rockwell is in a sole-source position for FY

1991–93. An improved version, the Hellfire Optimized Missile System (HOMS), will be produced by Martin Marietta Corporation.

The Hellfire program began advanced development in 1972 with competitive prototyping. In 1974, Rockwell won a development contract for a tri-service laser seeker and entered FSD in 1976. Martin Marietta submitted an unsolicited proposal for a low-cost alternative seeker that had been developed privately, and Martin Marietta won a competition over Rockwell in 1977. The technology to develop Hellfire was essentially available at the time of development; the development program did not greatly push the state of the art. The development program took much longer than is typical for an air-to-surface missile. Reasons cited in the SAR for FSD delays include "reduction of RDT&E funding, delays in procurement funding, and delays in testing caused by late delivery of hardware and correction of deficiencies revealed in earlier tests."

The Army was delegated authority for Milestone III, and Hellfire was approved for production in March 1982. Initial production contracts were awarded in FY 1982 to Rockwell for missile buses and to Martin Marietta for seekers. Later that year, it was decided to have both contractors produce the whole system in order to have competition. Each contractor produced a limited number of complete systems ("all-up-rounds") for certification in 1983, and head-to-head competition began in 1984. In order to keep the production base intact for both contractors, a split-buy strategy was adopted. In the first year of competition, each contractor was guaranteed at least 40 percent of the buy. From FY 1985 through FY 1988, each contractor was guaranteed a 25-percent share of the buy. Each contractor was allowed to build in the cost of establishing the production line into the missile buys.

The two prime contractors at first alternated in winning the larger shares of the buys. Still, major components, including the warhead, body, gyros, and rocket motor are still supplied by a single vendor. Martin Marietta tried to qualify a second source to compete with the rocket motor producer. However, on the threat of competition, the original producer lowered its prices to the point where it was not worthwhile to have competition. Martin Marietta has been successful in qualifying a second source for the missile control section. More recently, Rockwell has won the total quantity and is the sole producer for FY 90-93.

The HOMS began development in July 1989 and is slated to begin production in May 1993. We have not included funding for this program in our estimates. We also have not included funding for Longbow Hellfire, which is broken out for reporting purposes as a separate program and does not have enough data to be included in this study.

The development period (Milestone II to IOC) was about ten years. The schedule was delayed by about two years during FSD, due to funding reductions and delays in testing caused by late delivery of hardware and correction of deficiencies revealed in earlier tests. Problems in production start-up delayed production validation testing for six months. The system satisfies all its mission requirements except missile weight. At 99.8 pounds, it is 4.8 pounds over its required weight, and it was not considered feasible to reduce the weight without degrading performance.

The program appears to have been successful. Development cost growth was low, only 22 percent. Production cost growth was 60 percent. Competition did not obviously reduce costs, but it also did not increase them and probably contributed to the stability of the program.

9. Tube-launched, Optically-tracked, Wire-guided (TOW) and TOW 2 Missiles

TOW is a crew-portable or vehicle-mounted heavy anti-tank weapon. The basic TOW program began advanced engineering development in April 1963. Hughes designed the system and has been the principal producer of the missile and launcher. Initial production contracts were awarded to Hughes for missiles and launchers in November 1968 and to Chrysler Corporation for missiles in January 1969. IOC, as measured by first unit equipped, was achieved in September 1970. Hughes won a winner-take-all competition against Chrysler in November 1971.

A two-step TOW improvement program was initiated in August 1979 to meet the threat of advanced enemy armor. The first step, improved TOW, added a larger warhead with better performance against armor. Planned quantities of improved TOW missiles were not procured before initiation of step two, TOW 2. A development contract for TOW 2 was awarded to Hughes Aircraft Company in December 1978. The design features a larger warhead with a probe, thermal beacon, and improved flight motor designed to defeat the frontal armor of Soviet battle tanks. A microprocessor-based digital missile guidance set provides improved guidance. TOW 2 was approved for full-scale production in September 1981.

TOW schedule delays during advanced development and FSD amounted to about two years, but it was still possible to complete the program (advanced development to IOC) in about seven years. The main factors in development delays were a delay in completing development of the missile container, and low reliability factors.

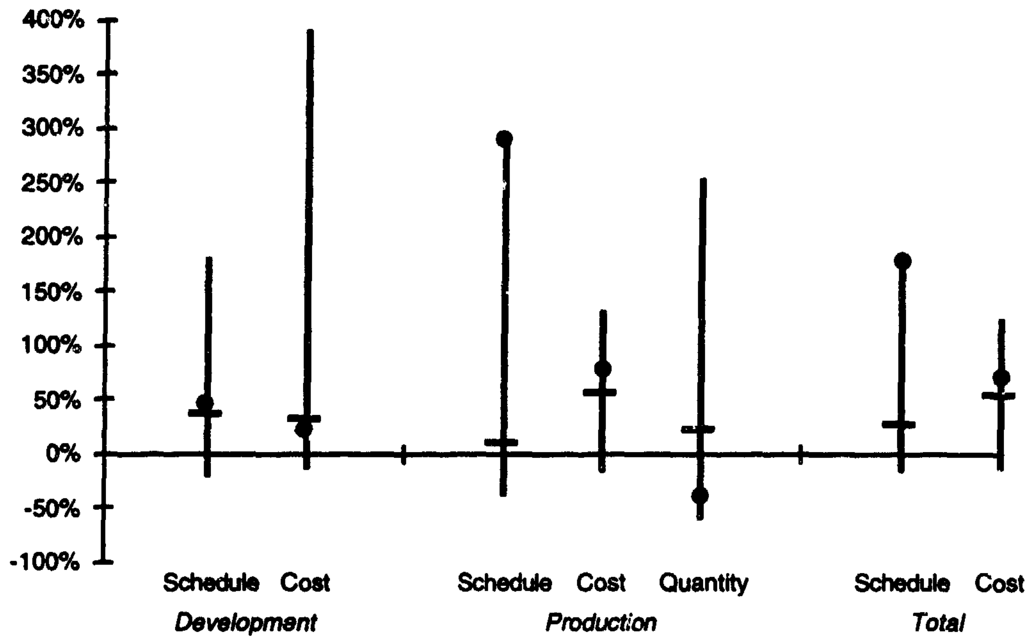

Figure III-14. Outcome for the TOW Missile

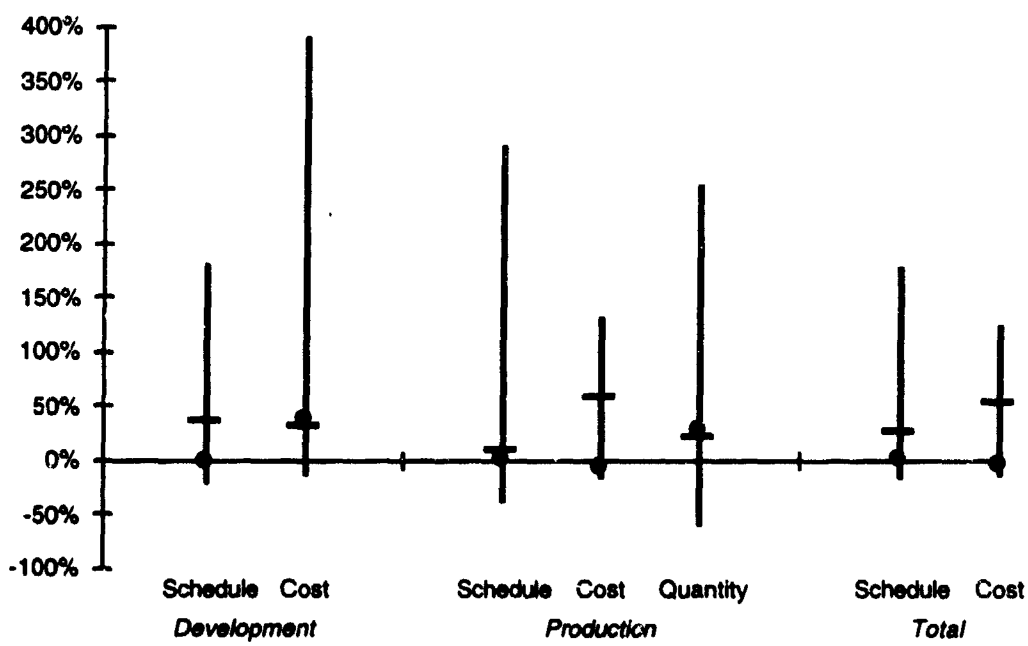

Figure III-15. Outcome for the TOW 2 Missile

Total TOW production quantity for the Army decreased from 232,614 missiles to 137,275. These drastically reduced procurement quantities were probably a key factor in the high rate of production cost growth. The production schedule did not correspondingly decrease, but, in fact, substantially increased. Thus, production schedule stretch is high, 290 percent.

TOW followed a dual-source acquisition strategy, with split buys between Hughes and Chrysler Corporation. After a winner-take-all competition, multiyear procurement contracts were awarded to Hughes in 1971 and 1975.

The technical performance of both TOW and TOW 2 is highly successful. The TOW is within 10 percent of the development estimate weight and met all other operational requirements. TOW 2 has met all weight, range, and reliability requirements, and accuracy has exceeded requirements. Development cost growth of 39 percent is due to engineering changes for the TOW 2A and TOW 2B enhancements, according to the program manager. There has been no production cost growth.

The TOW program defined the threat and operational/technical requirements early in the process, and technologies were limited to those considered to be proven. Modifications were implemented incrementally. Concept development took place in a competitive environment; procurement included dual-sourcing and multiyear procurement. "Should cost" studies were used to evaluate competitive bids. Competitive or dual-sourcing of launcher and night sight were also employed. Despite all this, total program costs grew 71 percent. Among the factors that went wrong are program stretchout, a drastic reduction in quantities procured, and problems in development of the thermal night sight.

The TOW 2 program was right on schedule. It achieved a rapid development schedule, with some development cost growth due to engineering changes. The production line was stopped in 1984 for non-compliance with Military Standards. Nonetheless, adherence to the planned production schedule and increased quantity contributed to low production cost growth.

10. Multiple Launch Rocket System (MLRS)

The MLRS program employed an unusual acquisition strategy in several respects. The development program was multinational, and the schedule was concurrent and accelerated. MLRS was successful. The development program was completed on time with a minimum of cost growth, and a multiyear production contract has contained costs in production. Total program costs are actually 10 percent below plan.

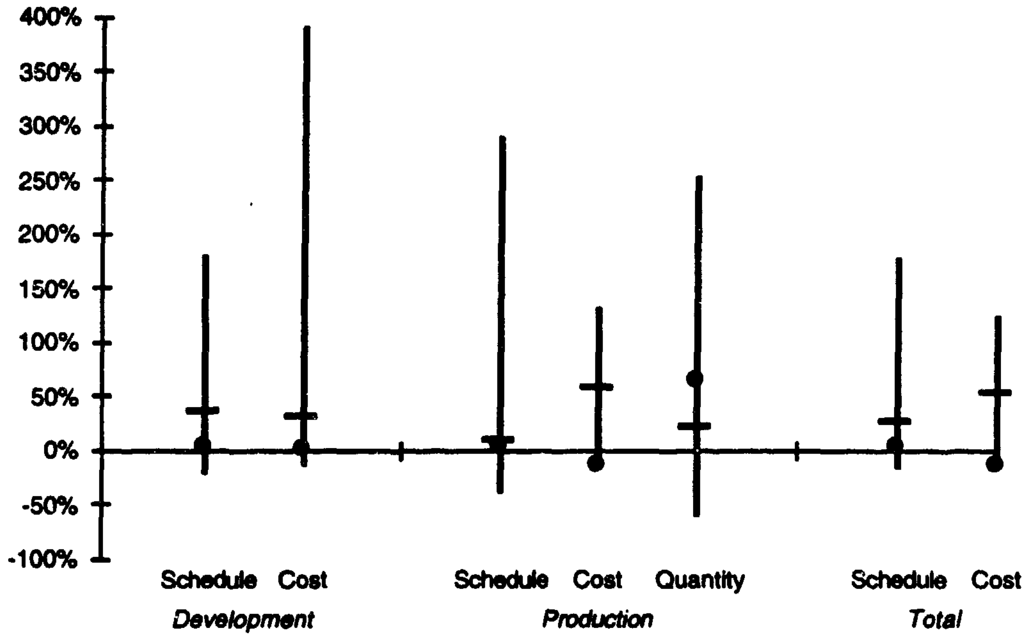

Figure III-16. Outcome for the MLRS

MLRS is an Army system designed to deliver firepower quickly against critical, time-sensitive targets. The Army began development in the mid-1970s and awarded five concept definition contracts in March 1976. A Milestone I review was held in January 1977. The Secretary of Defense directed the Army to continue studying means of accelerating the program and to give high priority to standardizing the weapon system for the North Atlantic Treaty Organization (NATO). A combination of manpower shortages and the need to counter large numbers of Soviet weapons made the program an Army-wide priority. The program enjoyed strong congressional support. In fact, Congress provided $5 million in FY 1977 for the program, $4 million more than the Secretary of Defense had requested. The program office resolved to set modest technical goals and then exceed them [11]. The Army's plan for acceleration provided for advanced development, but full-scale engineering development (FSED) only if required. If development risks appeared tolerable after the validation phase, production could begin without FSED.

The initial design process was iterative. The government rejected a strategy of providing only general specifications and concluded that the Missile Command had more detailed technical knowledge than any single contractor. Thus, the government called for an iterative, cooperative design process.

Because of the urgency of the program, the program manager received some dispensations from standard procedures. Some routine reports and meetings were omitted, and lawyers and contract specialists were assigned to the program full-time, rather than having to be drawn from a pool shared by other contract specialists.

In 1977, two contractors, the Boeing Company and Ling-Tempco-Vought (LTV) Aerospace and Defense Company were selected to build prototype launched systems with associated flight test equipment and hardware. The competitive shoot-off had good results. LTV was selected as the prime contractor for the maturation/initial production phase in May 1980. DSARC III was held in May 1980; the normal Milestone II review was omitted because of the acceleration of the program. The technology used was relatively simple. The Army was willing to accept performance somewhat less than planned to field a system quickly.

There was a five-year contract awarded to LTV in September 1983, following a should-cost analysis. The multiyear contract, with options, covered all self-propelled launchers/loaders and rockets for the life of the program as approved at that time. The GAO concluded that the multiyear contract had saved $166.8 million, due to purchasing certain raw materials and components earlier, and in more economical quantities, than would have been done under annual contracts. A second multiyear contract was awarded in June 1989 covering the FY 1989-1993 buys. The multiyear contracts probably contributed to the stability of the program.

The MLRS program exhibited little development schedule growth and schedule delay was only three-months (to satisfy a German requirement for a scatterable mine warhead). In July 1979, a memorandum of understanding (MOU) covering the intended adoption of MLRS was signed by France, Germany, the United Kingdom, and the United States. The contractor believes that the international nature of the program helped to maintain its stability. IOC slipped only 4 months from the original estimate, but the definition of IOC changed. The initial SAR defined IOC as eighteen launchers with 60 rockets per launcher, while the final definition was nine launchers with 60 rockets per launcher.

The demonstrated technical characteristics of system accuracy and maximum range are below the planning estimate. However, the December 1980 SAR reported that the existing maximum range was acceptable, and that it would not be cost-effective to make the changes required to increase it.

Both the U.S. and its allies used MLRS during Operation Desert Storm. According to the 1992 SAR, the system "performed extremely well...when significant numbers of MLRS launchers were deployed. All significant requirements were met, and in most cases exceeded for readiness, reliability, accuracy, and maintainability."

The best estimate of cost growth for this program, and the one used in this study, is from Reference [5]. We did not update this estimate, because of the difficulty of deriving cost-quantity relationships. Standard data sources group the prices of the launchers and the rockets into one dollar amount. The quantity of rockets per launcher changed over the course of the program, so it is difficult to develop an appropriate price-improvement curve. In the study documented in [5], IDA obtained detailed data on rockets and launchers and developed separate price improvement curves based on these data. The production cost growth estimate based upon those price improvement curves is used in this study.

Several lessons were learned from the MLRS experience:

1. Threat analysis led to a climate for MLRS to be developed under a priority system, including concurrency. While this is often a recipe for cost growth, in the case of the MLRS, the strategy was successful. The technology was kept simple. Even though the desired accuracy was not obtained, the Army has been able to field an acceptable system relatively quickly to fill a significant need.
2. The competitive prototyping produced systems that had good early test results.
3. The multiyear contract produced real cost savings, according to GAO, and also contributed to program stability.
4. The international nature of the program may have contributed to the political support it received and to its financial stability.

11. Summary

In this section, we examine key reasons for the specific program outcomes observed here. We group programs into low, medium, and high categories for development schedule growth and total program cost growth.

a. Reasons for Schedule Growth in Development

Table III-1 summarizes the key program characteristics that led to low, medium, or high schedule growth in development. Development is highlighted here, because it clearly represents a program outcome—it is important that the system be finished on time. Schedule growth in production, by contrast, is often a policy variable—e.g., Congress decides to slow the program for budgetary reasons.

Table III-1. Characteristics of Programs With Schedule Growth in Development

Program	Percentage growth	Characteristics
Low Growth		
TOW 2	0%	Follow-on system
Sidewinder AIM-9M	1%	Follow-on system to fulfill goals of AIM-9L Learned from unrealistic estimate of prior system
MLRS	6%	Urgent program Competitive prototype Requirements/schedule tradeoff made in favor of schedule
Medium Growth		
Maverick AGM-65A	33%	Vigorous testing program, low concurrency Total package procurement
Harpoon	35%	Urgent program—37 months planned, 50 months actual Contractor experience with anti-ship concepts High concurrency
Hellfire	44%	Vigorous testing program Competitive prototype
TOW	45%	Prototype Delay in development of missile container Reliability problems
Phoenix AIM-54C	46%	High concurrency Technical problems (eventually dual sourced to resolve problems)
Sparrow AIM-7M	49%	Competitive prototype High launch rate during testing
HARM	59%	Prototype, but underestimated technical difficulty Strict phasing—resolved problems before procurement funds were committed Expanded requirement for frequency and aerodynamic mobility

Table III-1. Characteristics of Programs With Schedule Growth in Development (continued)

Program	Percentage growth	Characteristics
High Growth		
Phoenix AIM-54A	94%	Problems resolved in development, not allowed to spill over into production Testing delays Delays in aircraft platform
Maverick AGM-65D/G	98%	Funding cut slowed development, allowed technology to catch up Prototype Vigorous testing program
AMRAAM	129%	Prototype showed infeasibility of approach High concurrency, urgent program Rushed testing
Sidewinder AIM-9L	148%	Urgent program, with fly-before-buy strategy Technical problems, with increased development quantity Joint service program, with technical disagreements
Sparrow AIM-7F	180%	Underestimation of technical difficulty (vacuum tube to solid state) Vigorous testing program

Two of the three programs with low development schedule growth—the TOW 2 and the Sidewinder AIM-9M—were modification programs with fairly simple technologies. The other program, the MLRS, was urgent and made a technical tradeoff to meet the schedule. Programs with high development schedule growth included two joint-service programs (AIM-9L and AIM-7F) and two programs with schedule urgency (AGM-65D/G and AIM-9L). Underestimation of technical difficulty was common. In two cases (AIM-54A and AIM-9L), development was slowed to resolve technical problems, in the hope that they would not spill over into production. In the case of the Phoenix AIM-54A, that strategy appeared to be successful. In the case of the Sidewinder AIM-9L, we cannot be sure that the high production cost growth was due to development problems spilling over into production because the AIM-9L also suffered a major production stretchout.

b. Reasons for Cost Growth (Total Program)

Table III-2 summarizes the key program characteristics that led to cost growth outcomes, based on the case analyses. As in the previous analysis, programs are grouped into low, medium, and high categories.

All four programs with the lowest TPCG are characterized by low stretch in production. Interestingly, three of the four programs in this group were also characterized by urgency. In the case of the MLRS, the requirement was modified to meet a deadline. (The AIM-9M may be something of an anomaly in this group, because it was intended to fulfill the technical goals for the AIM-9L.)

The programs with high TPCG, by contrast, were characterized by stretched production schedules. Both AMRAAM and the Phoenix AIM-54C had high levels of concurrency and rushed testing programs. Both the Phoenix AIM-54C and the Sidewinder AIM-9L were dual-sourced for technical reasons (e.g., to get a better functioning system) rather than principally for cost savings. In the case of the AIM-54C, funding was reduced to move more quickly to the next-generation system, and five years were spent qualifying a second source for only two years of head-to-head competition, with resulting inefficiencies. AMRAAM also had used a dual-sourcing strategy and was produced at less than the planned rate—an expensive combination. The Sparrow AIM-7M also suffered from reduced production funding in order to fund the next-generation system.

Table III-2. Characteristics of Programs With Cost Growth In Total Program

Program	Percentage growth	Characteristics
Low Growth		
MLRS	-10%	Competitive prototype Requirement lowered because of time urgency Mulityear procurement, low stretch
Maverick AGM-65A	1%	Total package procurement with low concurrency Vigorous testing program Low stretch
TOW 2	-4%	Urgent modification program Foreign Military Sales Low stretch
Sidewinder AIM-9M	10%	Learned from schedule problems in AIM-9L program Urgent program, took its lumps in development Low stretch
Medium Growth		
Phoenix AIM-54A	38%	Took lumps in development Low stretch
Hellfire	46%	Slowed development due to funding cut Dual-sourcing Competitive prototype
TOW	71%	Production stretch a problem despite prototyping and multiyear procurement
Maverick AGM-65D/G	42%	Vigorous testing program Prototype Dual-sourcing with buyout
HARM	52%	Strict phasing Prototype, but underestimated technical difficulty Threat of production competition
Sparrow AIM-7F	73%	Underestimated technical difficulty Took its lumps in development Vigorous testing program
Harpoon	66%	Crash program Underestimated production Costs at FSD

Table III-2. Characteristics of Programs With Cost Growth in Total Program (continued)

Program	Percentage growth	Characteristics
High Growth		
AMRAAM	84%	Prototype showed infeasibility of approach High concurrency, rushed testing Stretched program, dual-sourcing
Phoenix AIM-54C	89%	High concurrency Dual-sourced for technical reasons Five years qualifying for two years of competition Needed funding for next generation
Sparrow AIM-7M	100%	Competitive prototype, low cost growth in development Needed funding for next generation
Sidewinder AIM-9L	123%	Crash program Dual-sourced for technical reasons Production stretch

C. LESSONS LEARNED FROM TACTICAL AIRCRAFT PROGRAMS

1. Development

Tactical aircraft outcomes in both development and production exhibited less variability than the outcomes of tactical missiles. Development cost growth ranged from 5 to 53 percent, and total program cost growth ranged from -9 to 40 percent. In part, this may be because our sample of aircraft is smaller than the sample of missiles. However, it is also the case that development programs of aircraft appear to proceed more smoothly than those of other types of systems [2 and 5].

Development schedule growth was small in the aircraft development programs. The highest value was 18 percent for the F-14A.

The two programs with the lowest development cost growth are the F-5E and the F-15A/B. The F-5E was a relatively simple development program, building on a commercial system. The F-15 program proceeded smoothly, with relatively few engineering changes. The F-14A had the highest development cost growth, 53 percent. This may have been due to the unusual contracting arrangement, a fixed-price development contract with options for several years of production. Grumman ran into cost trouble and insisted on changes in the contract before it would produce the aircraft.

2. Production

Few studies have analyzed aircraft production. One reason may be that "the production phase is assumed to be less interesting as outcomes at this point are more predictable than during development, and the problems that do occur are generally traceable to faulty decisions made earlier in the program" [6, p. 159].

But from the contractor's viewpoint, production opportunities define the business environment contractors face. A contractor cannot keep going on developments alone. According to Mayer, "without existing or potential production work, contractors scale back investment, reduce staffing, and redirect efforts toward other markets that have a brighter outlook."

As compared with the 1950s, the 1990s have fewer new production starts, fewer production lines open at any given time, and longer production runs, but with smaller total quantity—i.e., a lower production rate. None of these trends, of course, is at all favorable to reducing costs.

During the 1960s, we saw a trend toward fewer new production starts. However, the Vietnam War greatly increased the demand for aircraft, and production buys were quite large. The space program also helped to keep those contractors who were frozen out of the new airframe business going. In the 1970s, several new programs started, but annual buys were reduced after the war ended. In the 1980s, many new programs started, but not all of them survived. The 1990s will be a decade where only a few prime contractors for tactical aircraft will survive.

The A-X program has already been canceled, and it appears that the F-22 and the F/A-18E/F may be the only tactical aircraft programs in production by the end of the decade. Several systems currently in production—the F-14, the F-15, and the F-16—are expected to end within the next few years.

Nevertheless, one characteristic of the production environment is that production lines tend to stay active much longer, even as the total number of units produced declines. Table III-3 shows the average length of production runs for fighter and attack programs. Continuing these trends and combining it with a trend toward fewer new programs provides further weight to the conclusion that fewer units will be produced per year and that contractors who fail to participate in one of the few new programs will no longer be prime contractors. A model cited in Reference [6] projected that a company would lose its viability as a prime contractor after only 18 months without a contract, after which it would be forced to focus on subcontracting.

Table III-3. Average Length of Production Runs for Air Force and Navy Fighters

Years	Length (Years)
1951-1960	9.4[a]
1961-1970	20.0
1971-1980	18.0

Source: Reference [6].

[a] Excludes the F-5 fighter, which was built primarily for export.

In our sample of tactical aircraft, there was considerable variation in production schedule stretch. The F-5E program, for example, produced its planned quantity 30 percent faster than planned, while the F-14A and AV-8B programs were stretched out, producing at about half the planned rate.

With respect to cost, the F-5E came in 21 percent under expected cost, benefiting from a high production rate and technical simplicity. However, both the AV-8B and the

F-14A suffered from production stretch, yet exhibited low production cost growth. In the case of the F-14A, slower production was accompanied by funding cuts. The original plan, to produce 463 aircraft in 5.5 years, was recognized early as unrealistic, and the contractor had plenty of time to scale back production facilities. Moreover, the development of the F-14D aircraft occurred at about the same time, and may have helped the contractor cope with costs on the F-14A. In the case of the AV-8B, the program never produced as many aircraft as planned. However, the presence of other, larger programs in the same plant—including the F/A-18 and the F-15—may have helped to contain costs.

The program with the highest production cost growth is the F/A-18, which exhibited production cost growth of 42 percent, despite little production stretch. The F/A-18 originated as the losing entry in a competition to provide a lightweight fighter for the Air Force and the Navy. The Air Force selected the YF-16 in a prototype flyoff over the YF-17. Congress encouraged the Navy to adapt the YF-16 to its special needs. However, the Navy redesignated the YF-17 as the F-18. Technical problems in range, cycle time, strafing, roll, and faulty radar images were identified at the DSARC III meeting. Despite claims that the digital flight control system would eliminate the need to physically change the test aircraft (because changes would be made in the software), the Navy and the contractor made more physical changes to the F-18 than to any other fighter aircraft in the last twenty years [12]. Technical changes, particularly late in development or in production, are expensive.

IV. COST/SCHEDULE RELATIONSHIPS

A. INTRODUCTION

This chapter describes the regression analyses used to illuminate the relationship between cost and schedule growth in ongoing acquisition programs. The relationships can be used to project the effect of schedule changes on cost. Relationships are presented for development, production, and the total program for tactical missiles and tactical aircraft.

B. METHODS

We used several analytical tools to construct development equations for this diverse group of systems, including linear and log-linear regression, weighted regression, and correlation analysis. Examining the relationship between cost and schedule growth in development, we concluded that it was not appropriate to consider the major independent variable, DSG, to be exogenous. Other variables determine DSG. Therefore, we estimated the tactical missile development relationship as a simultaneous system of equations.

We considered the possibility that the relationship between development cost growth and development schedule growth may not be linear. We expect that, as the development schedule stretches beyond plan, development costs would increase. However, we also expect that compressing the development schedule would increase costs. Thus, the true relationship is probably U-shaped. However, in our tactical missile data set, the only system that had a compressed development schedule was the Pershing 2, where a 17-percent speedup was accompanied by 13 percent cost growth. For the tactical aircraft, the data set was judged to be too small to do more than single-equation estimation.

The dependent variables were the cost growth measures described in Chapter II. The candidate independent variables, along with the areas in which they are used, are listed in Table IV-1. The variables include several variants of schedule. (These variables are defined more fully in Chapter II.) They also include some variables relating to program management, including program characteristics and acquisition initiatives (e.g., design-to-cost, multiyear procurement, and total package procurement). In addition, variables describing the size of the program in terms of planned cost were used. Data for the non-schedule supplemental variables are provided in Appendix A.

Table IV-1. Candidate Independent Variables

Variable	Notation	Definition	Development	Production and Total
Schedule Variables				
Planned development schedule	PDS	Planned time to develop the first version of the system, measured in months from Milestone II to IOC	X	
Actual development schedule	ADS	Actual time to develop the first version of the system, measured in months from Milestone II to IOC	X	
Development schedule growth	DSG[a]	Ratio of the actual development schedule to the planned development schedule	X	
Development schedule growth, predicted	DSGHAT	Predicted value of DSG in missile model (see section IV.B.)	X (missiles only)	
Planned production schedule	PPS	Planned time to produce the planned quantity of the system, measured in months from Milestone III to the end of production of the planned quantity		X
Actual production schedule	APS	Actual time to produce the planned quantity of the system, measured in months from Milestone III to the end of production of the planned quantity		X
Production schedule stretch	PSS	Ratio of the actual production schedule to the planned production schedule		X
Planned total schedule	PTS	Planned time to develop and produce the system, measured in months from Milestone II to the end of production of the planned quantity		X
Actual total schedule	ATS	Actual time to develop and produce the system, measured in months from Milestone II to the end of production of the planned quantity		X
Total schedule growth	TSG	Ratio of the actual total schedule to the planned total schedule		X

[a] DSG is also used as a dependent variable in the simultaneous model for missiles.

Table IV-1. Candidate Independent Variables (continued)

Variable	Notation	Definition	Development	Production and Total
Program Variables				
Development quantity growth	DQG	Measure of growth in the development quantity	X	
Modification program	MOD	1 if the program is a modification program, 0 otherwise	X	X
Competition in full-scale development	CFSD	1 if competition (dual or multiple sources) was used in FSD, 0 otherwise	X (missiles only)	
Design-to-cost	DTC	1 if design-to-cost was applied, 0 otherwise	X	X
Total package procurement	TPP	1 if total package procurement was used, 0 otherwise	X (missiles only)	X (missiles only)
Incentives in full-scale development	IFSD	1 if contract incentives were used in full-scale development, 0 otherwise	X	
Prototype	PRO	1 if a prototype was developed before full-scale development, 0 otherwise	X	X
Competition in production	CPROD	1 if competition (dual or multiple sources) was used in production, 0 otherwise		X (missiles only)
Multiyear procurement	MYP	1 if a multiyear procurement contract was used, 0 otherwise		X
Fixed-price development	FPD	1 if fixed-price development was used, 0 otherwise	X	X
Full-scale development start	FSDST	The year of full-scale development start, used as a proxy for technological complexity	X	X
Concurrency	CONC	Percentage of test program remaining to be completed at Milestone III (see Reference [9])	X (missiles only)	X (missiles only)
Intercept missile dummy	IMD	1 if an intercept missile, 0 otherwise	X (missiles only)	X (missiles only)
IIR Maverick dummy	IIRMD	1 if an IIR Maverick (AGM-65D/G), 0 otherwise	X (missiles only)	X (missiles only)
AV-8B dummy	AV8BD	1 if an AV-8B, 0 otherwise	X (aircraft only)	X (aircraft only)
e AV-8B Dummy	EAV8B	ϵ (= 2.71828) if an AV-8B, 1 otherwise	X (aircraft only)	X (aircraft only)

Table IV-1. Candidate Independent Variables (continued)

Variable	Notation	Definition	Development	Production and Total
Total Cost Variables				
Planned development cost	PDC	Planned cost to develop the system, measured in millions of FY 1994 dollars from Milestone II to the end of development of the first version	X	
Planned total cost	PTC	Planned cost of the total system at the Development Estimate, measured in millions of FY 1994 dollars from Milestone II to the end of production of planned quantity	X	X
Planned unit cost	PUC	Planned cost to produce a unit at the Development Estimate, measured in millions of FY 1994 dollars	X (missiles only)	X (missiles only)

Equation formulations that appeared on the surface to be successful sometimes had to be discarded because of high correlations of the independent variables. For example, several of the acquisition initiatives were highly correlated with various schedule variables. Because our purpose here was to develop cost/schedule relationships, we generally dropped the initiative variables and left the schedule variables in the equation when choices had to be made. The only initiative variable retained was a multiyear procurement variable in the equation for tactical missile production cost growth. The initiatives may still be important influences on acquisition costs and schedules.

C. TACTICAL MISSILES

1. Development

This section discusses the development relationships for tactical missiles. The development cost growth database consisted of the twenty programs whose outcomes are displayed in Chapter II. The dependent variable was the development cost growth ratio for spending from Milestone II to the end of development of the first version, DCGM2.

As previously indicated, lack of data prevented us from examining the case of a development schedule more compressed than planned, since there was only one such case in the data set. If data were sufficient, we could allow for this effect by using a quadratic term or a non-linear specification. However, linear specifications best depicted this data set.

Because the DSG and DCG equations comprised a simultaneous system, we used the two-stage least squares method of estimation. (Detailed descriptions of the method can be found in econometrics texts such as [13] and [14].) The first equation was estimated using ordinary least squares, and the predicted value of DSG from Equation 1 (DSGHAT) was calculated for each observation. Then, DSGHAT was used as the independent variable in Equation 2.

$$\text{DSG} = 1.6325 - \underset{(.02)}{(.0095 \times \text{PDS})} + \underset{(.05)}{(.2056 \times \text{DQG})} + \underset{(.04)}{(.4038 \times \text{IMD})} + \underset{(.07)}{(.7128 \times \text{IIRMD})} \qquad (1)$$

$$\text{Adjusted } R^2 = .578 \qquad \text{SEE} = .344$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of variation in DSG explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

Equation 1 contains the following variables:

- PDS, planned development schedule. The lower this estimate (the more schedule optimism), the higher the DSG ratio. This variable is statistically significant at the .02 level.
- DQG, development quantity growth. Having to build unplanned development items is an indicator of technical problems and impending schedule growth. The coefficient is positive and statistically significant at the .05 level.
- IMD, the air intercept dummy variable, is positive and significant at the .04 level. Notably, the two systems with the highest DSG, the AIM-7F and the AIM-9L, are both air intercept missiles.
- IIRMD, the IIR Maverick dummy, is positive and significant at the .07 level. This variable is included to remove the effect of the IIR Maverick, which is atypical of the rest of the data. It has an unusual administrative delay in FSD that did not appear to be due to technical problems.

Using the coefficients from Equation 1, predicted values for DSG, dubbed DSGHAT, were obtained. This variable was used as an independent variable in the DCG equation (Equation 2), along with IIRMD.

$$DCG = -1.366 - \underset{(.03)}{(1.5972 \times IIRMD)} + \underset{(.0001)}{(2.034 \times DSGHAT)} \quad (2)$$

$$\text{Adjusted } R^2 = .631 \qquad SEE = .638$$

The development cost growth model in Equation 3 has DSG as the dependent variable. Equation 4 has DCG as the dependent variable. These equations can be used to predict development cost growth in ongoing acquisition programs.

Plots of actual versus fitted values are included as Figure IV-1 (DSG model) and Figure IV-2 (DCG model). In each case, a 45-degree reference line indicates the points at which actual and fitted values would be equal. Points above the line were overestimated; points below the line were underestimated.

The simultaneous model can be used to provide estimates, both at Milestone II and beyond, of schedule and cost growth. Suppose that we are trying to project the outcome of an air intercept missile program with an estimated schedule of 80 months. Therefore, PDS = 80 and IMD = 1. Because we have no reason to think that the development quantity estimate is incorrect, we set DQG = 1. Because we do not expect an arbitrary schedule hold similar to the IIR Maverick, we set IIRMD = 0. This yields a schedule growth estimate of 1.4819, or 48 percent schedule growth. To project cost growth, set IIRMD = 0 and DSGHAT = 1.4819, and calculate the value from Equation 2. This indicates potential development cost growth of 1.6482.

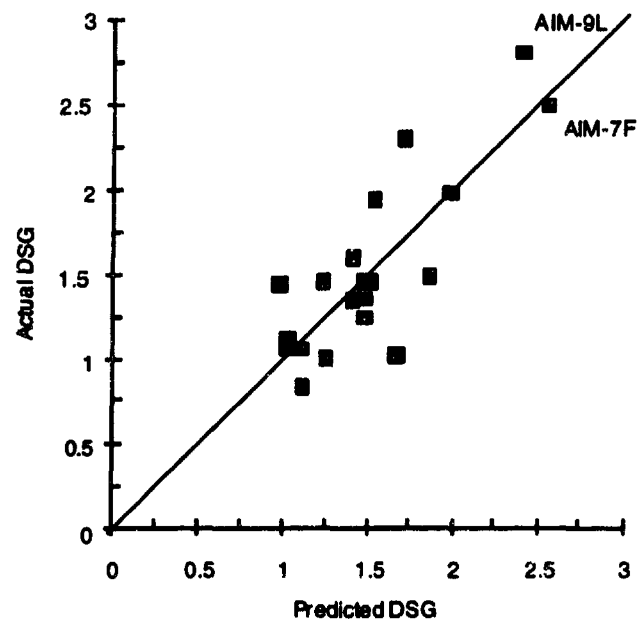

Figure IV-1. Development Schedule Growth for Tactical Missiles

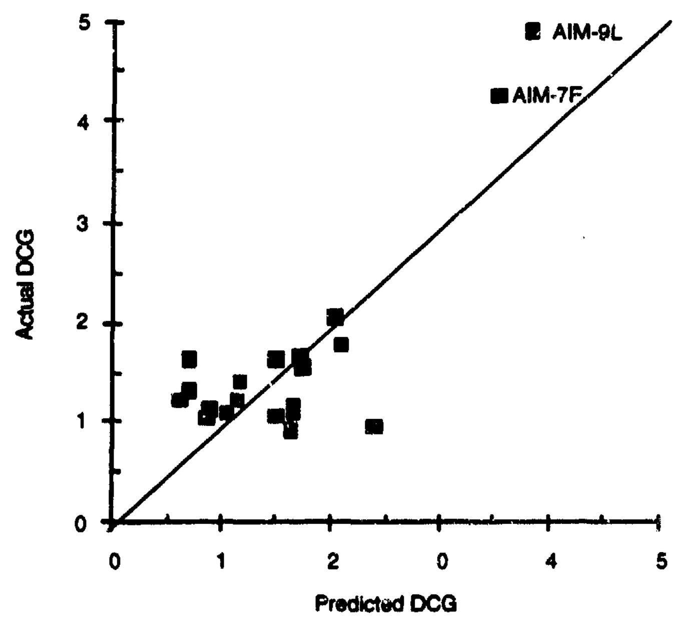

Figure IV-2. Development Cost Growth for Tactical Missiles

As the program progresses, the value of DQG may change. Suppose that during EMD the program has to build 10 percent more development items than planned. Then DQG becomes 1.10, and the values of DSG and DCG can be recalculated. The new projected schedule growth is 50 percent, and the new projected cost growth is 69 percent.

To supplement the simultaneous model, we also include a simple, single-equation model that estimates DCG as a function of DSG and DQG:

$$DCG = -.1427 + \underset{(.04)}{(.3776 \times DSG)} + \underset{(.0001)}{(.9094 \times DQG)} \qquad (3)$$

$$\text{Adjusted } R^2 = .920 \qquad \text{SEE} = .303$$

Equation 3 can be used to predict development cost growth as the program progresses. The fit of the equation is shown in Figure IV-3.

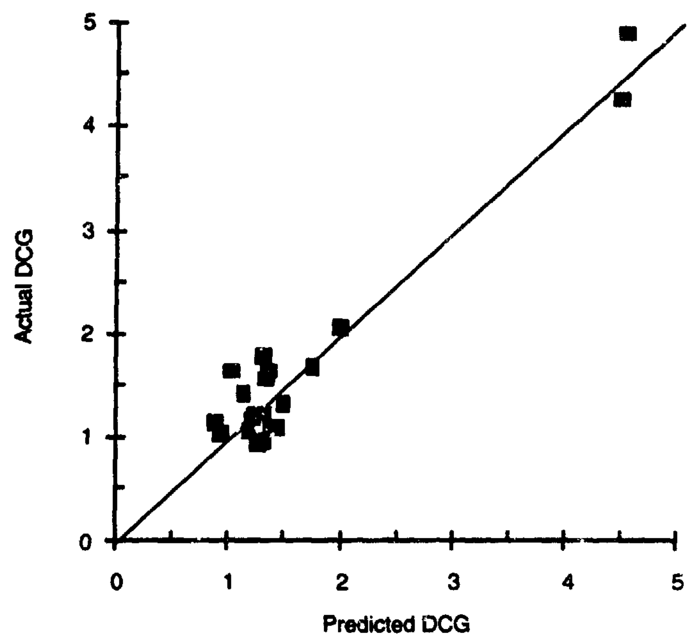

Figure IV-3. Single Equation Model for Development Cost Growth for Tactical Missiles

2. Production Relationship for Tactical Missiles

The best-fitting equation (Equation 4) includes production stretch positively, as expected. Planned unit cost, a proxy for complexity, also enters positively. The programs with multiyear procurement (MLRS, TOW, TOW 2, Patriot, Improved Hawk, and Shillelagh) had significantly lower production cost growth. Examination of this equation indicated no problems with multicollinearity or with individual cases driving the relationship.

$$PCG = 1.11 + \underset{(.006)}{(.2858 \times PSS)} + \underset{(.03)}{(.2321 \times PUC)} - \underset{(.07)}{(.3124 \times MYP)} \qquad (4)$$

$$\text{Adjusted } R^2 = .458 \qquad \text{SEE} = .298$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of cost growth variation explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

The fit of the equation is shown in Figure IV-4.

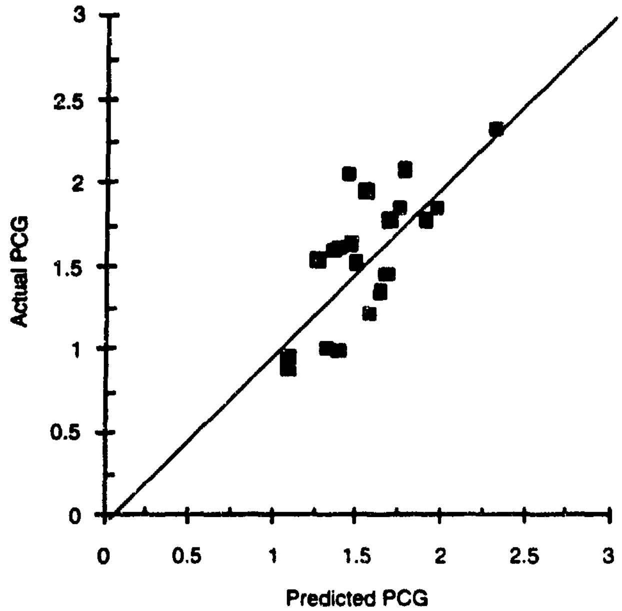

Figure IV-4. Production Cost Growth for Tactical Missiles

An alternative equation (Equation 5) contains concurrency as a measure. While it is not statistically significant, concurrency was found in the case analyses to be an important contributor to cost growth. The equation also uses development cost growth as an independent variable. Programs that have had high development cost growth are more likely to have high production cost growth. Equation 5 could be used as a check of the other equation.

$$PCG = .9512 + \underset{(.08)}{(.2143 \times PSS)} + \underset{(.07)}{(.1199 \times DCG)} + \underset{(.12)}{(.4147 \times CONC)} \qquad (5)$$

$$\text{Adjusted } R^2 = .344 \qquad SEE = .236$$

To use the production cost growth equations, consider a new system with planned unit production cost of \$500,000 (\$0.5 million in FY 1994 dollars), no production stretch expected, and no multiyear procurement. Set PSS = 1, PUC = .5, and MYP = 0. The production cost growth projection from Equation 4 is 1.51. To use Equation 5, additional data are necessary. Suppose that the program is expected to have 50 percent cost growth in development and 50 percent concurrency. Then DCG = 1.5 and CONC = .5. This results in a cost growth projection of 1.55. As the program goes on, suppose that schedule stretch of 50 percent occurs. For example, the production schedule could grow 50 percent with no corresponding increase in production quantity. Alternatively, the quantity could be cut by one-third with no corresponding decrease in schedule. Setting PSS = 1.5 yields different projections of production cost growth: 1.65 from Equation 1 and 1.66 from Equation 2.

3. Total Program Cost Growth for Tactical Missiles

In developing the total program relationship for tactical missiles, we included the same candidate variables as were used in production. We added total schedule growth (TSG). The best equation is:

$$TPCG = .7645 + \underset{(.005)}{(.3677 \times TSG)} + \underset{(.04)}{(.1845 \times PUC)} + \underset{(.04)}{(.2729 \times IMD)} \qquad (6)$$

$$\text{Adjusted } R^2 = .500 \qquad\qquad SEE = .259$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of cost growth variation explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

The fit of this equation is good, as seen in Figure IV-5, and signs of the coefficients are reasonable. As seen in both development and production, schedule growth is associated with cost growth. There are no apparent problems with multicollinearity or with individual cases driving the relationship.

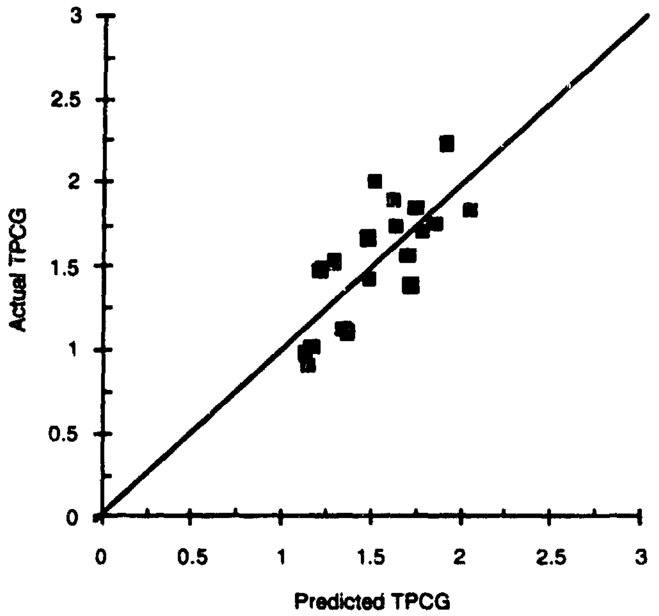

Figure IV-5. Total Program Cost Growth for Tactical Missiles

D. AIRCRAFT

1. Development Cost Growth

The aircraft development regression is different from that for the tactical missiles. Aircraft programs typically receive more management attention than tactical missiles programs and they are larger in terms of cost. Moreover, perhaps because of the widespread use of contractor labor across the United States, they are unlikely to be allowed to fail.

As previously noted, development cost growth for aircraft is lower in percentage terms and shows less variation than for tactical missiles. The raw relationship between development cost growth and development schedule growth is not strong. However, a regression weighted by planned development cost (in millions of FY 1994 dollars) provided reasonable results. The regression also includes a dummy variable for the AV-8B (AV8BD). The AV-8B is distinctive in two ways. It is the only modification program among the seven tactical aircraft in the database. It also had a slow ramp-up to full-rate production [15]. In all program phases, the relationship of cost growth to schedule growth in the AV-8B is atypical. In development, the AV-8B had schedule growth of only 3 percent but cost growth of 40 percent. Because we cannot be certain that the effect we are observing is common to all tactical aircraft modification programs, or is distinctive to the AV-8B, we have labeled the variable AV8BD rather than MOD. The development cost/schedule relationship for tactical aircraft is:

$$DCG = .-1.135 + \underset{(.0006)}{(2.1614 \times DSG)} + \underset{(.01)}{(.3514 \times AV8BD)} \qquad (7)$$

$$\text{Adjusted } R^2 = .860 \qquad\qquad SEE = 2.86$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of cost growth variation explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

Regression was weighted by planned development cost in FY 1994 dollars. A scatter plot of DSG and DCG showing the fit of the equation is shown in Figure IV-6.

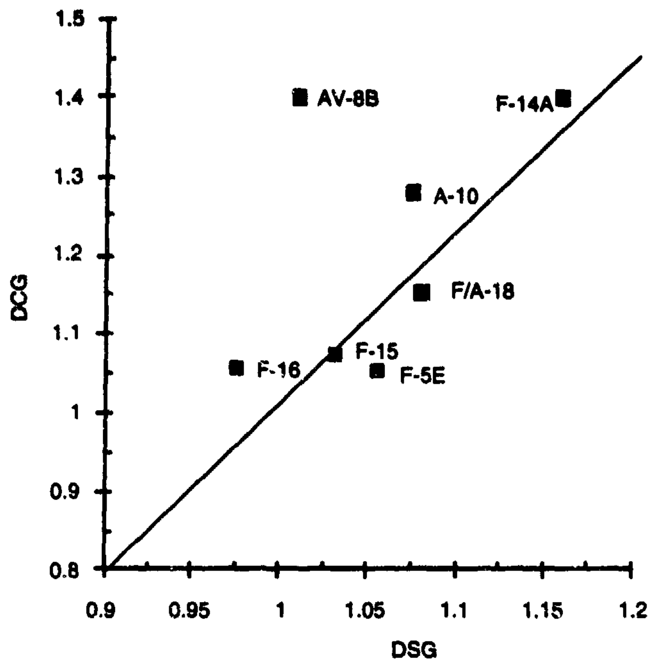

Figure IV- 6. Development Cost Growth for Tactical Aircraft

2. Production Cost Growth

In the case of production cost growth, the strongest relationship was a logarithmic one. The regression was run in linear form on the logarithms of the variables. The dependent variable was the log of the production cost growth ratio, LNPCG. The independent variables included the log of the number of months required to produce the planned quantity, LNAPS, and the AV8BD variable.

The equation is shown here transformed back to arithmetic space. The constant term includes a correction to account for the bias of the logarithmic form, as does the R^2 statistic. This process is described in Appendix B. In arithmetic space, the AV-8B dummy variable changes its form. It takes the value *e* for the AV-8B and 1 for all other aircraft. To avoid confusion with AV8BD, we have called this variable EAV8B. The arithmetic transformation of the equation is:

$$PCG = .2678 \times \underset{(.004)}{APS^{.3286}} \times \underset{(.02)}{EAV8B^{-.3942}} \qquad (8)$$

$$\text{Adjusted } R^2 = .845 \qquad\qquad SEE = .086$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of cost growth variation explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

Figure IV-7 is a scatter plot of PCG and APS showing the fit of the equation. The equation has a reasonable standard error. Again, the AV-8B's unusually slow ramp-up did not have as large a cost penalty as was typical of the rest of the group.

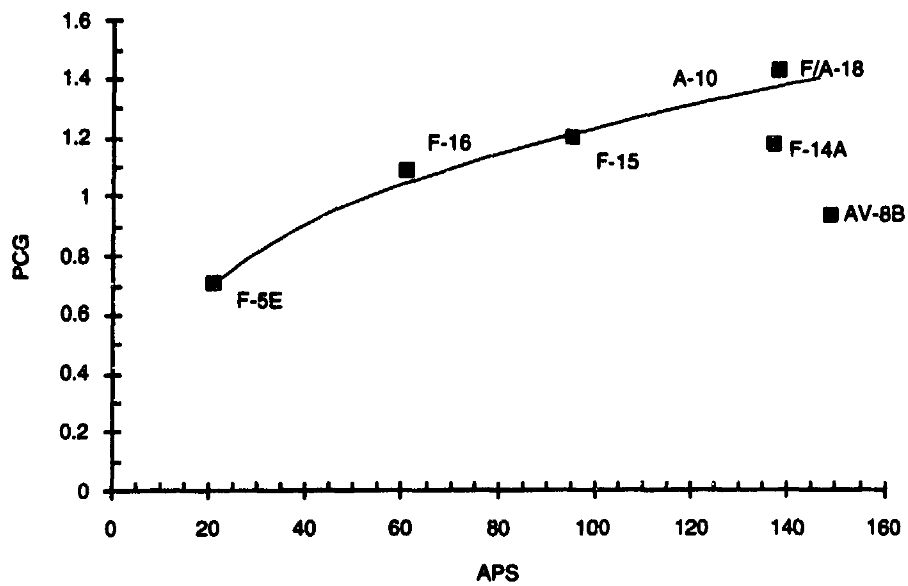

Figure IV-7. Production Cost Growth for Tactical Aircraft

3. Total Program Cost Growth

We also estimated a total program relationship for tactical aircraft. As with production, the preferred relationship includes a measure of total schedule rather than schedule growth and also includes a dummy variable for the AV-8B. Also, similar to the production equation, the total program equation is in logarithmic form. It was estimated using the logarithms of the variables, then transformed back into arithmetic space. It includes a corrected constant term to account for the bias of the logarithmic equation form. As estimated, the dependent variable, LNTPCG, was the natural log of the total program cost growth ratio, and the independent variables included the natural log of the total schedule in months and AV8BD.

As with the production relationship, the total program cost growth equation is shown here transformed back to arithmetic space. The constant term includes a correction to account for the bias of the logarithmic form. In arithmetic space, the AV-8B dummy variable changes its form. It takes the value e for the AV-8B and 1 for all other aircraft. To avoid confusion with AV8BD, we have called this variable EAV8B. The arithmetic transformation of the equation is:

$$TPCG = .3785 \times \underset{(.003)}{ATS^{.2365}} \times \underset{(.006)}{EAV8B^{-.3262}} \tag{9}$$

$$\text{Adjusted } R^2 = .890 \qquad\qquad SEE = .053$$

Numbers in parentheses below the coefficients are significance levels. Adjusted R^2 is the percentage of variation in TPCG explained by the model, adjusted to reflect the number of independent variables, and SEE is the standard error of the estimate.

Figure IV-8 is a scatter plot of TPCG and ATS showing the fit of the equation.

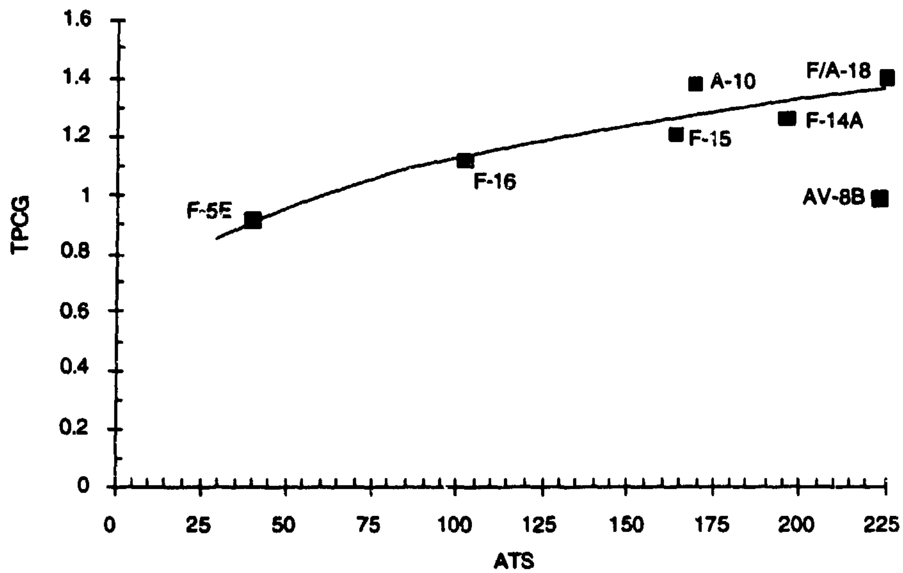

Figure IV-8. Total Program Cost Growth for Tactical Aircraft

E. DISCUSSION AND SUMMARY

Using standard techniques, we were able to estimate regressions that describe the relationship between cost and schedule for tactical missiles and tactical aircraft. We were able to derive separate equations for development and production, as well as an overall equation relating total program cost growth to the program schedule.

The tactical missile regressions generally fit well, with intuitively correct signs. They can reasonably be used for getting a sense of the cost implications of schedule changes. The only exception is that the development relationship should not be used for predicting the cost implications of significantly speeding up development. The tactical missile relationships indicate the feasibility of the approach and the usability of the projection tools. However, in the tactical aircraft, it is difficult to make inferences based on only seven observations. Additional data development work is needed to make the aircraft regressions into practical projection tools.

V. SUMMARY AND CONCLUSIONS

This paper reports on the beginning of an effort to describe cost and schedule growth patterns associated with the acquisition of major systems, to identify reasons for the growth, and to develop a way to anticipate likely growth in development and early production phases. By looking at past acquisition programs, we examined what separates the kinds of programs completed on schedule and within cost plans from those that experience cost and schedule growth.

Tactical missile programs were selected for a pilot effort, largely on the basis of data availability. Cost and schedule growth were measured in development and in production. These measures showed a great deal of variability among the 20 programs examined. Programs took from 50 months to 137 months from Milestone II to IOC. Only two of the tactical missile programs were finished on time. The program with the highest development schedule growth exceeded its plan by 180 percent. Two programs came in under budget, while two others doubled in cost from their Milestone II plan.

Selected tactical missile programs were examined in more detail to determine the reasons for schedule and cost growth. Keys to preventing schedule growth in development are technical realism and willingness to make tradeoffs. Programs with high development schedule growth tended to underestimate technical difficulty. Two of the five programs with high DSG also had high overall cost growth. However, in three of the five cases of high DSG, it appeared that a strictly phased approach—resolving problems in development when spending levels are low—resulted in lower levels of overall cost growth. Keys to preventing overall cost growth are correctly estimating the degree of technical difficulty in the programs and maintaining the planned production schedule. Programs that employed a high degree of concurrency, that had to be dual-sourced for technical reasons or that were dual-sourced at less than full rate had high cost growth. In one case, the threat of competition appeared to reduce costs.

There were enough common factors in the tactical missiles to suggest that estimating quantitative relationships would be possible. The equations presented here relate cost growth to schedule growth in development and production. In development, a simultaneous model links an estimating relationship for schedule growth with a cost growth equation. The major determinant of development schedule growth was quantity growth (the need to produce more items for testing than planned). Other variables in the DSG equation were the planned schedule for the program and dummy variables for intercept missiles and for one outlier. The results of this equation feed into a DCG equation. Cost growth in production was linked to schedule stretch, planned unit cost (a proxy for complexity), and multiyear procurement. These equations can be used to identify programs likely to experience future growth, as well as to monitor the effect of schedule changes on cost growth. The relationships can be used to identify which programs require more detailed examination.

Cost and schedule growth measures were also calculated for a sample of seven tactical aircraft. These measures are less dispersed than those for tactical missiles. The aircraft programs tended to receive more management attention and more protection from schedule stretch than the tactical missiles. The highest cost growth index was 1.40, versus 2.23 for the tactical missiles. Quantitative relationships were also developed for this group, but the small sample size requires that they be regarded as tentative. This exercise indicated that the cost/schedule relationships look different for different equipment types.

In the light of these results, we conclude that DoD and other personnel who review acquisition programs would benefit from a review method based on detailed information about the strategies and outcomes of past programs. This is the first step for development of such a review method that examines the reasonableness of program plans and assesses the effect on cost of schedule changes.

The case analyses of tactical missiles also indicate that many useful lessons can be gleaned from historical perspective, lessons that cannot always be captured in a quantitative estimating relationship. At the beginning of a weapon system development program, the feeling often prevails that the program is unique and will somehow avoid repeating the problems of past programs. Yet cost and schedule growth persist. Despite individual differences in programs, the importance of understanding the level of technical difficulty when original schedule and cost estimates are made, of strict phasing and vigorous testing, and of adhering to production plans are borne out by analysis of past strategies and outcomes.

APPENDIX A

DATA USED IN REGRESSION ANALYSES

Table A-1. Tactical Missile Data

Variable	Phoenix AIM-54A	AMRAAM	Hellfire	HARM	Sparrow AIM-7F	TOW	Sidewinder AIM-9L	TOW 2	Harpoon	Maverick AGM-65D/G	Sparrow AIM-7M	Sidewinder AIM-9M	Phoenix AIM-54C	Improved Hawk	Shillelagh	Pershing II	Patriot	Lance	Maverick AGM-65A	MLRS
PDS	69	48	88	44	45	62	33	61	37	58	39	79	85	78	92	71	123	38	42	71
ADS	134	110	127	70	126	90	82	61	50	115	58	80	124	97	97	59	137	55	56	75
PPS	108	127	79	72	68	73	41	108	87	75	51	57	86	77	55	35	125	56	86	100
APS	111	347	78	84	51	285	94	110	144	145	55	37	64	160	90	62	270	53	84	106
PTS	177	175	167	116	113	135	74	169	124	133	90	136	171	155	147	106	248	94	128	171
ATS	245	457	305	154	177	375	176	171	194	260	113	117	188	257	137	121	407	108	140	181
TSG	1.38	2.61	1.23	1.33	1.57	2.78	2.38	1.01	1.56	1.95	1.26	0.86	1.1	1.66	1.27	1.14	1.64	1.15	1.09	1.06
DQG	0.82	0.66	0.95	1	3.94	1.01	4.1	1	1	0.94	1	1.94	1.5	1	1.38	0.82	0.83	1.09	0.91	0.77
MOD	0	0	0	0	1	0	1	1	0	1	1	1	1	1	0	1	0	0	0	0
CFSD	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
DTC	0	1	1	1	0	0	1	0	1	1	1	1	0	0	0	1	1	0	0	1
TPP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
IFSD	0	0	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	0	1
PRO	0	1	1	1	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	1
CPROD	0	1	1	0	1	1	1	0	0	1	1	1	1	0	1	0	0	0	0	0
MYP	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	1	0	0	1
FPD	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FSDST	62	82	76	78	66	63	71	78	73	76	78	76	77	64	59	79	72	67	68	77
CONC	0.42	0.53	0	0.57	0		0		0.41	0			1	0.41			0		0.21	
IMD	1	1	0	0	1	0	1	0	0	0	1	1	1	1	0	0	1	0	0	0
IIRMD	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
PDC	417	1,165	535	460	97	406	46	123	979	255	111	76	162	357	489	1,066	3,628	1,498	449	524
PTC	2,756	9,922	1,330	3,607	1,809	3,455	787	3,045	3,138	2,809	1,968	874	871	2,486	1,762	2,264	15,204	2,412	1,417	4,806
PUC	1	0.36	0.03	0.23	0.18	0.01	0.08	0.02	0.75	0.08	0.17	0.11	1.01	0.32	0.01	3.04	1.21	0.86	0.06	0.01

Table A-2. Tactical Aircraft Data

Variable	A-10	AV-8B	F-14A	F-15	F-16	F-5E	F/A-18
PDS	53	72	50	66	41	18	80
PPS	64	77	66	83	55	30	118
PTS	117	149	116	149	96	48	198
TS	169	223	196	164	102	40	225
TSG	1.444	1.497	1.69	1.101	1.063	0.833	1.136
DQG	0.71	1	2	1	1	1	1
MOD	0	1	0	0	0	0	0
CFSD	0	0	0	0	0	0	0
DTC	1	1	0	0	1	0	1
TPP	0	0	0	0	0	0	0
IFSD	1	1	1	1	1	1	1
PRO	1	1	0	0	1	1	0
CPROD	0	0	0	0	0	0	0
MYP	0	1	0	0	1	0	0
FPD	0	0	1	0	0	0	0
FSDST	73	79	69	70	75	72	76
AV8BD	0	1	0	0	0	0	0
EAV8B	1	2.71828	1	1	1	1	1
PDC	1,012.1	1,770.3	3,371.9	5,951.9	1,474.9	345.8	3,684.2
PTC	7,070.6	11,209.5	22,815.7	23,612.5	12,061.6	1,081.7	22,407.1
PUC	8.31	28.09	42	24.23	16.29	8.97	23.4

APPENDIX B

STATISTICAL CORRECTION FOR BIAS IN LOGARITHMIC SPECIFICATIONS OF EQUATIONS FOR TACTICAL AIRCRAFT PRODUCTION AND TOTAL PROGRAM COST GROWTH

APPENDIX B.

STATISTICAL CORRECTION FOR BIAS IN LOGARITHMIC SPECIFICATIONS OF EQUATIONS FOR TACTICAL AIRCRAFT PRODUCTION AND TOTAL PROGRAM COST GROWTH

The cost/schedule relationships for tactical aircraft production and total program costs employed logarithmic specifications. These relationships had the final forms:

$$PCG = .2678 \times \underset{(.004)}{APS^{.3286}} \times \underset{(.02)}{EAV8B^{-.3942}}$$

$$\text{Adjusted } R^2 = .845$$

$$TPCG = .3785 \times \underset{(.003)}{ATS^{.2365}} \times \underset{(.006)}{EAV8B^{-.3262}}$$

$$\text{Adjusted } R^2 = .890$$

as indicated in Chapter IV. The purpose of this appendix is to show how these final forms were derived.

These relationships have the generic form:

$$Y = a_0 \times X_1^{a_1} \times X_2^{a_2}$$

where Y is the dependent variable and X_1 is an independent variable. X_2 is an independent dummy variable set equal to e for the observation of interest (in this case the AV-8B) and 1 otherwise. The quantities a_0, a_1, and a_2 are parameters to be estimated.

To estimate the parameters, analysts typically linearize by taking natural logarithms of both sides of the equation and adding an error term u, giving:

$$\ln Y = a_0' + a_1 \times \ln X_1 + a_2 \times \ln X_2 + u.$$

The dummy variable $\ln X_2$ is thus in the familiar 0/1 form, and the equation to be estimated is linear. Note that a_1 and a_2 retain the same form, and estimates from the linear regression can be substituted directly into the multiplicative equation. However, the constant term a_0 changes form—it becomes a_0', or $\ln a_0$. Given an estimate of a_0' from the linear regression, the logical estimator of a_0 is $e^{a_0'}$. This estimate of the original constant term a_0 inherits the desirable asymptotic properties from the linear regression, including consistency and asymptotic efficiency. It does not, however, inherit the small sample properties, particularly unbiasedness. (Unbiasedness is desirable, because it ensures that the expectation of the mean of $e^{a_0'}$ is equal to a_0.)

To correct for the bias in the estimator $e^{a_0'}$, we applied a smearing estimate correction factor recommended in [16]. The estimate of the adjusted coefficient of determination (R^2) was also corrected. The procedure is:

1. Calculate the unadjusted predicted values of Y using the estimates from the linear regression—a_1, a_2, and $e^{a_0'}$.
2. Calculate the actual/predicted ratio for each observation and find its mean.
3. Multiply $e^{a_0'}$ by the factor calculated in step 2. The result is the adjusted constant term.
4. Using the adjusted constant term, re-calculate predicted values for Y, the error sum of squares (ESS), and the total sum of squares (TSS).
5. Calculate:

$$R^2 = 1 - (ESS/TSS)$$

and

$$\text{Adjusted } R^2 = 1 - [(T-1)/(T-K)]\,(1 - R^2)$$

where T is the number of observations and K is the number of independent variables.

The better the fit, the less difference the adjustment makes. In our equations, the adjustment made a difference of less than 1 percent in the constant term and less than 3 percentage points in the adjusted R^2. The unadjusted equations were:

$$PCG = .2672 \times \underset{(.004)}{APS^{.3286}} \times \underset{(.02)}{EAV8B^{-.3942}}$$

$$\text{Adjusted } R^2 = .870$$

and

$$TPCG = .3782 \times \underset{(.003)}{ATS^{.2365}} \times \underset{(.006)}{EAV8B^{-.3262}}$$

$$\text{Adjusted } R^2 = .893$$

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ABBREVIATIONS

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AAAM	Advanced Air-to-Air Missile
AMRAAM	Advanced Medium-Range Air-to-Air Missile
DAB	Defense Acquisition Board
DoD	Department of Defense
DSARC	Defense Systems Acquisition Review Council
DSG	development schedule growth
DT&E	development test and evaluation
ECCM	electronic counter-countermeasures
FLIR	forward-looking infrared
FOT&E	follow-on test and evaluation
FSD	full-scale development
FSED	full-scale engineering development
GAO	General Accounting Office
HARM	High-Speed Anti-Radiation Missile
HOMS	Hellfire Optimized Missile System
IDA	Institute for Defense Analyses
IIR	imaging infrared
IOC	initial operational capability
IOT&E	initial operational test and evaluation
MOU	memorandum of understanding
MTBMA	mean time between maintenance actions
NATO	North Atlantic Treaty Organization
OPEVAL	operational evaluation
OSD	Office of the Secretary of Defense
PAUC	procurement average unit cost
R&D	research and development
RFP	request for proposals
SAR	Selected Acquisition Report
TECHEVAL	technical evaluation
TPP	total package procurement

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This paper reports on the beginning of an effort to describe cost and schedule growth patterns associated with the acquisition of major systems, to identify reasons for the growth, and to develop a way to anticipate likely growth in development and early production phases. Tactical missile programs were selected for a pilot effort. Cost and schedule growth were measured, and reasons for such growth were identified for selected cases. Next, quantitative relationships were developed to relate cost growth to schedule growth in development and production. These relationships can be used by OSD analysts and others to support major milestone reviews by examining the reasonableness of program plans and assessing the cost impact of schedule changes. Cost and schedule growth measures were also calculated for a small sample of tactical aircraft, and some tentative quantitative relationships were developed for this group.

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